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REVIEW

Environmental remediation and the efficacy of ceramic membranes in wastewater treatment—a review

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Abstract

Ceramic membranes are gaining rapid traction in water and wastewater treatment applications due to their inherent advantages, such as chemical/thermal stability, low fouling propensity, and extended lifespan. This review paper provides a comprehensive overview of ceramic membranes, exploring their composition, fabrication techniques, filtration principles, and diverse applications. Various types of ceramic membranes, including alumina, zirconia, titania, silica, and zeolite, are discussed. As global challenges related to water scarcity and pollution intensify, the implementation of ceramic membranes offers a sustainable and effective approach for water and wastewater treatment and safeguarding vital water resources. Despite the dominance of polymeric membranes in the field, the constant pursuit of reduced production costs and the apparent benefits of ceramic membrane are fueling their rapid growth. The review also examines applications that demonstrate the effectiveness of pressure-driven ceramic membrane technology for treating industrial wastewaters from diverse industries, including textile, pharmaceutical, and petrochemical. While the technology shows efficiency in various wastewater treatment scenarios, future research should focus on optimizing investment costs through new fabrication technologies, improving selectivity, permeability, and packing densities, minimizing fouling, and proposing scale-up strategies based on experimental research results. The collective findings reveal the potential of ceramic membranes to revolutionize wastewater treatment and environmental remediation.

Keywords Ceramic membranes · Wastewater treatment · Environmental remediation · Membrane fouling · Ceramic applications

1 Introduction

Environmental degradation is without a doubt one of the biggest issues that the civilization is now facing. Prioritizing environmental sustainability through wastewater treatment is one of the Sustainable Development Goals (SDG) of the UN. However, in recent years, global challenges related to water scarcity, water deficit, and industrial activity–related water pollution have grown in importance [1, 2]. In recent decades, there has been an increase in the need for clean water for domestic consumption. This need has been exacerbated by climate change, an expanding global population, and rapid urbanization [3]. The world population growth has led to the increase in water stress and the contamination of environmental waters [4]. People all over the world face major health hazards due to the rising number of organic contaminants being released into sources of drinking water. Due to growing waste discharge, population growth, industrial advancements, and a lack of comparable water supplies, water contamination has become a major concern [5]. Examples of some of the numerous alarming contaminants include particulate matter, heavy metals, pesticides, herbicides, fertilizers, oil spills, poisonous gases, industrial effluents, sewage, and organic compounds [6]. Therefore, it is extremely desirable to use efficient, recyclable, economical, and ecologically friendly methods to remove these dangerous contaminants from effluents.

In recent years, the issue of environmental degradation and its impact on the planet have gained increasing attention from scientists. There is an increasing need to research and put into practice practical solutions to lessen the negative effects and restore ecological equilibrium since human activities continue to emit dangerous compounds into the

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environment [7–10]. In this context, the significance of environmental remediation becomes paramount as it assumes a crucial role. In order to safeguard living systems and the environment from further degradation and to ensure a sustainable future, environmental remediation involves reducing or removing pollutants or contaminants from a variety of environmental media, including air, water, soil, and sediments. [11]. The objective of this review paper is to explore the current state of environmental remediation and highlight the latest advancements in this field, by presenting a comprehensive overview of the subject matter, providing valuable insights into the importance of environmental remediation and its potential to mitigate environmental pollution and promote a sustainable future.

Traditional methods of wastewater treatment involve a combination of physical, chemical, and biological processes and operations to remove solids, organic matter, and sometimes nutrients from wastewater [10]. Each process serves a distinct purpose, with the physical treatment focusing on the elimination of impurities through diverse mechanical approaches. An example of this is adsorption, a process in which contaminants attach to a solid surface, efficiently extracting them from the water [12]. Another efficient method is the advanced oxidation process (AOP), employing powerful oxidizing agents to degrade and remove both organic and inorganic pollutants [13] Membrane separation, a commonly employed physical technique, utilizes semi-permeable barriers to selectively permit the passage of water molecules while hindering impurities [14]. This method encompasses various techniques including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. There are various well-known chemical oxidation processes utilized in different catalytic applications. However, the AOP is regarded as a vital method in wastewater treatment. AOPs encompass a range of techniques that share similar principles, generating oxidizing agents such as hydroxyl radicals (●OH) [13, 15]. Potential oxidation processes include electrochemical oxidation, photo-electrochemical oxidation, UV-assisted Fenton oxidation, and ozonation [10, 16]. Biological wastewater treatment utilizes microorganisms to decompose organic pollutants through a range of techniques, including the activated sludge process, trickling filters, and anaerobic digestion [10]. Although biological techniques are acknowledged for being environmentally friendly and effective, their selection depends upon the precise type and composition of wastewater to ensure optimal performance and sustainability in water treatment. These wastewater treatment techniques present inherent limitations that require careful consideration during their application. Despite the effectiveness of membrane filtration in removing diverse contaminants, it can be excessively costly due to the rapid clogging of membranes [17]. While coagulation and flocculation processes are effective, they present challenges in terms of sludge volume management, leading to elevated costs. Moreover, chemical techniques, although rapid and efficient, may not be economically feasible for small enterprises, thus limiting their practicality [10]. Biological treatment, valued for its cost-effectiveness, requires a substantial duration and depends on the ideal conditions for microbial growth [18].

These methods can be categorized into several stages, such as preliminary, primary, secondary, and tertiary treatment. The preliminary treatment involves the elimination of coarse solids and other large materials that are found in raw wastewater including grit, oil, grease, large floating, and suspended solid matter [19]. The primary treatment marks the initial stage in the wastewater treatment plant, aiming to eliminate a substantial portion of the organic particulate matter present in the wastewater [20]. This process entails the removal of settleable organic pollutants and inorganic solid particulate matter through a sedimentation process, accompanied by the elimination of floating materials through skimming. Secondary treatment of wastewater removes colloidal organic matter by biological processes employing bacteria and other microorganisms and these microbial processes may be aerobic or anaerobic [21]. Its primary objective is to oxidize the readily biodegradable biochemical oxygen demand (BOD) that eludes primary treatment and to achieve additional removal of suspended solids [20]. Tertiary treatment, often referred to as the final "polishing" stage, is implemented to further enhance the quality of effluents from secondary treatment processes [22]. The primary goals of tertiary treatment include the removal of fine suspended solids and dissolved inorganic solids and eliminating the last traces of organics.

Different types of materials can be employed in environmental remediation and therefore a wide variety of approaches can be exploited for this purpose. Because of the intricate combination of various substances, their tendency to evaporate easily, and their limited reactivity, tackling the containment and breakdown of environmental contaminants, is demanding. Therefore, recent research has concentrated on utilizing ceramics to create innovative solutions for environmental cleanup [23, 24]. Ceramics are pivotal in diverse environmental uses, encompassing tasks like detecting, observing, and measuring pollutants, as well as averting, managing, and rectifying their presence [25]. Many ceramics are being explored as catalysts for pollution prevention, control, and remediation applications [26]. Ceramic substances have become essential assets in the realm of environmental remediation because of their distinct characteristics and adaptable uses. Constructed from inorganic substances like oxides, carbides, and nitrides, these materials provide specific benefits in tackling a range of environmental difficulties [27].

2 Wastewater treatment

2.1 Wastewater pretreatment

Pretreating wastewater helps break down the structure of macromolecules, increasing the availability of monomers for fermentation and improving biohydrogen production [28]. Several wastewater pretreatment methods are used to improve the availability of microbial-substrate interactions and enhance the rate of biohydrogen production. These techniques include mechanical treatments like ultrasonication, chemical treatments like alkaline and acidification, biological treatments like enzymatic and microbial treatments, and physical treatments like thermal and microwave treatments. [28, 29]. Physical pretreatment requires exposing the wastewater to high temperatures thermally and also radiation [30]. This encourages the larger organic components in the wastewater to react and become soluble. The physical pretreatment increases the substrate's temperature exposure, which speeds up the breakdown of organic compounds and increases wastewater treatment efficiency overall [28]. Electromagnetic waves include microwaves, which have frequencies between 300 MHz and 600 GHz [28]. In the process of microwave pretreatment, a microwave oven produces high- and low-intensity electric field resonant patterns that produce hot spots. These hot spots change the structure of macromolecules by breaking their hydrogen bonds via the alternating microwave electric field, which causes these molecules to hydrolyze and increases process efficiency by producing high temperatures [31]. Chemical pretreatment encompasses the use of chemicals such as acids, bases, and oxidizing agents. Such chemicals react with the contaminants in the wastewater, breaking down the polymeric bonds and increasing the readiness of the substrate for anaerobic degradation [32]. Wastewater pretreatment using H_2SO_4 is found to be more effective than nitric and hydrochloric acid in enhancing glucose utilization and hydrogen production [33]. Additionally, studies have looked into alkaline pretreatment with NaOH, which breaks down organic compounds and has demonstrated increased efficiency in the production of hydrogen [34]. Strong oxidizing agent ozone is used in two stages of wastewater pretreatment: the direct phase involves ozone reacting with wastewater constituents, and the indirect phase creates free hydroxyl radicals by means of a chain reaction [28, 35, 36]. High-efficiency mechanical pretreatment technology increases hydrogen production while consuming energy. In pretreated wastewater, ultrasonication produces cavitational effects that improve biodegradability, break down complex organic pollutants, and dramatically boost hydrogen production efficiency [29, 30]. Pretreatment involves treating the substrate with particular microorganisms prior to dark fermentation [37]. By releasing extracellular enzymes that break down complex organic molecules into soluble monomers, these microorganisms improve wastewater hydrolysis and produce more hydrogen. Examples of microorganisms used for pretreatment include white rot fungi like *Pleurotus eryngii*, *Coriolopsis* sp., and *Penicillium simplicissimum*, which have been applied in textile industrial wastewater and achieved significant organic removal [38–40]. Numerous studies have used enzymatic pretreatment with enzyme pellets to treat various kinds of wastewater [28].

2.2 Sources and types of wastewaters

Wastewater is water that has undergone changes in its physical, chemical, or biological attributes due to the introduction of certain substances, rendering it inappropriate for purposes like drinking, irrigation, industrial processes, or aquatic life support [41, 42]. Water holds immense value as one of the most invaluable resources globally. All forms of life, including plants and animals, rely on water for their survival. Given the finite nature of our available water resources, the processes of water treatment and wastewater treatment hold significant importance [43]. These water treatment processes aim to enhance water quality by eliminating a majority of pollutants from wastewater, thus addressing the issue of water scarcity [44].

Wastewater can be broadly categorized into two types: sewage wastewater and non-sewage wastewater [45]. Domestic sewage wastewater arises from everyday tasks within residences, educational institutions, and medical facilities. Conversely, non-sewage wastewater encompasses wastewater generated by industrial operations like factories

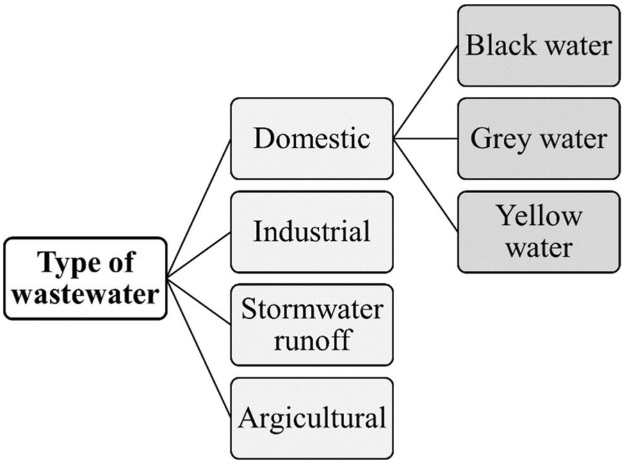


Fig. 1 Types of wastewater

and industrial facilities, along with stormwater and rainwater produced by precipitation or flooding incidents [46]. According to Fig. 1, there exist four distinct categories of wastewater; the initial category is domestic wastewater, which comprises the wastewater generated from everyday activities in residential dwellings, hotels, restaurants, schools, and shopping centers [47]. According to the illustration, household wastewater is divided into three distinct subcategories: black, gray, and yellow waters [24]. The most polluted variant is black water, which includes waste from toilets and kitchen sinks. Gray water is less polluted and originates, for instance, from sources like washing machines [48, 49]. Given that it contains numerous detergents and liquid soaps, it is not regarded as pathogenic. Yellow water refers to urine devoid of the additional pollutants found in black water and gray water. Because of its simpler composition, less complex treatment approaches are utilized. The second categorization is industrial wastewater, which consists of liquids generated from human activities related to the handling of raw materials and the manufacturing process [50]. Industrial wastewater constitutes one of numerous severe sources of water pollution, significantly compromising the aquatic environment [47]. The third category involves stormwater runoff, which refers to the excess water that flows across the Earth's surface during and following instances of precipitation, such as rain or melting snow. This runoff occurs when the soil's natural ability to absorb water is exceeded, leading the water to move over the terrain and frequently collect in watercourses, rivers, lakes, or other water bodies [49, 51]. The final classification pertains to agricultural wastewater, which is a significant contributor to water pollution. Agricultural runoff signifies the surplus water that drains away from fields during surface irrigation processes [52]. This drainage transports sediments and nutrients, resulting in the pollution of nearby water reservoirs. Furthermore, agricultural wastewater harbors pollutants like fertilizers, pesticides, and herbicides [53]. With the ongoing advancement of the economy and the enhancement of people's living conditions, there is a continuous rise in the quantity of wastewater requiring treatment [54].

2.3 Importance of wastewater treatment

Wastewater treatment holds significant importance due to a multitude of reasons. Firstly, it serves as a critical means of environmental protection by effectively removing or reducing pollutants present in wastewater [55]. These pollutants include various chemicals, pathogens, and nutrients. By eliminating them, wastewater treatment prevents water bodies from becoming contaminated and helps to preserve the balance of the aquatic ecosystems, thereby safeguarding natural environments [56]. Additionally, environmental preservation is achieved through wastewater treatment as it curbs the detrimental impact of untreated wastewater on aquatic ecosystems, soil quality, and biodiversity [57]. The health of people and animals may be seriously endangered by untreated wastewater. This is because the wastewater contains disease-causing germs. Wastewater treatment facilities successfully eradicate or neutralize these pathogens by the use of several treatment procedures, such as disinfection, hence limiting the spread of waterborne illnesses [58].

Wastewater treatment is essential to eliminate pollutants, preventing the contamination of natural water sources. Through proficient removal of physical, chemical, and biological pollutants like suspended solids, organic substances, nutrients, heavy metals, and harmful microorganisms, treatment procedures safeguard aquatic ecosystems and halt the accumulation of harmful substances [6, 59]. Furthermore, processed wastewater serves diverse purposes in sectors like municipal wastewater treatment, industry-specific industrial wastewater treatment, agricultural wastewater treatment for curbing chemical runoff, and stormwater management to avert flooding and the dissemination of pollutants amid intense rainfall [59–62]. Furthermore, water scarcity is addressed through safe wastewater reuse for non-potable purposes like irrigation and industrial processes [63]. One of the practical applications of wastewater treatment is the reuse of treated wastewater for agricultural purposes [64, 65]. In areas where water is scarce or freshwater resources are restricted, treated wastewater can become a valuable irrigation water source for crops [65]. Through thorough treatment procedures, the treated wastewater is purified, ensuring its suitability for agricultural use while avoiding health hazards or adverse environmental effects [66].

3 Membrane technology in wastewater treatment

3.1 Types of membranes

A membrane refers to a barrier that effectively separates two phases by selectively limiting the movement of components between them [67]. Membranes are generally classified as either isotropic or anisotropic [68]. Isotropic membranes exhibit a uniform composition throughout their volume, and as shown in Fig. 2, it can be further divided into microporous, nonporous dense films, and electrically charged membranes [69]. Isotropic membranes possess a consistent composition and physical structure. They may be microporous, enabling substantial permeation fluxes, or nonporous (dense), which restricts their applicability due to low permeation fluxes [70, 71]. Isotropic microporous membranes find common use in microfiltration, while anisotropic membranes exhibit non-uniform structures with distinct layers [72, 73]. These membranes consist of a thin selective

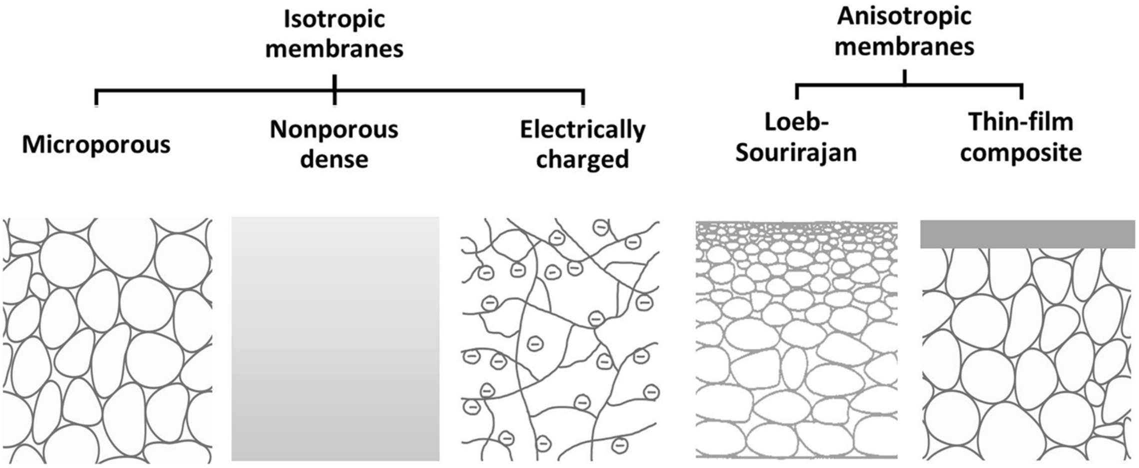


Fig. 2 Illustration of types of membranes

layer on top of a thicker and highly permeable layer, making them well-suited for reverse osmosis (RO) processes [67].

Composite membranes and Loeb-Sourirajan membranes are two distinct types of anisotropic membranes [74]. Anisotropic membranes, unlike isotropic ones, exhibit a non-uniform nature and composition [68]. Composite membranes and Loeb-Sourirajan membranes offer contrasting characteristics in terms of their chemical composition and structure [75]. Loeb-Sourirajan membranes feature a uniform chemical composition but display heterogeneity in terms of pore size [76]. On the other hand, composite membranes exhibit an inhomogeneous chemical composition and structure [75]. In the realm of water purification and treatment, the availability of diverse membrane technologies with variations in type, configuration, material, and matrix provides effective solutions for addressing various challenges [68, 74, 77].

There are two main categories of membranes based on their composition: organic and inorganic [78]. Organic membranes are predominantly composed of synthetic organic polymers and find extensive application in pressure-driven separation processes, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis [69]. Examples of synthetic organic polymers used in these membranes include polyethylene (PE), polytetrafluoroethylene (PTFE), polypropylene, and cellulose acetate, among others [67]. Contrarily, inorganic membranes consist of materials such as ceramics, metals, zeolites, or silica. These membranes exhibit excellent chemical and thermal stability, rendering them highly suitable for a range of industrial uses, including hydrogen separation, ultrafiltration, and microfiltration [79].

3.2 Categories of wastewater treatment

Membrane technology plays a significant role, contributing to over 50% of the global water treatment volume. The process of water purification entails the elimination of various pollutants, including organic, chemical, and biological contaminants, along with suspended solids, to achieve water that is clean and meets sensory standards [80]. Based on the membrane's pore size, pressure-driven technology encompasses four distinct processes: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). These processes strive to improve the effectiveness of wastewater treatment, leading to a more environmentally friendly production [81, 82]. Polymeric and ceramic membranes, employed in a variety of filtration techniques, demonstrate a spectrum of pore sizes, extending from compact to permeable membranes. These membranes can accommodate a range of filtration needs due to their diversity in pore sizes, providing possibilities for both fine and coarse filtration processes. The range of pore sizes affects the membranes' ability to separate substances according to their molecular sizes, which makes them effective tools in applications requiring exact control over filtration levels [83]. Pressure-induced membrane procedures employ the variance in pressure between the input and output sides as the primary impetus to propel the solvent (typically water) through the membrane [84]. These pressure-driven membrane processes can be categorized based on diverse factors, encompassing the size, form, and charge of the substances retained, as well as the pressure applied to the membrane [85]. This categorization identifies microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, as depicted in Fig. 3.

Microfiltration is a low-pressure physical separation technique employing a semipermeable membrane to eliminate suspended solids from a liquid flow. The membranes typically have pore sizes ranging from 50 to 500 nm and operate at relatively low pressures, typically between 0.02 and 0.5 MPa [86]. Widely utilized in integrated membrane reactors for desalination and heavy metals removal, microfiltration

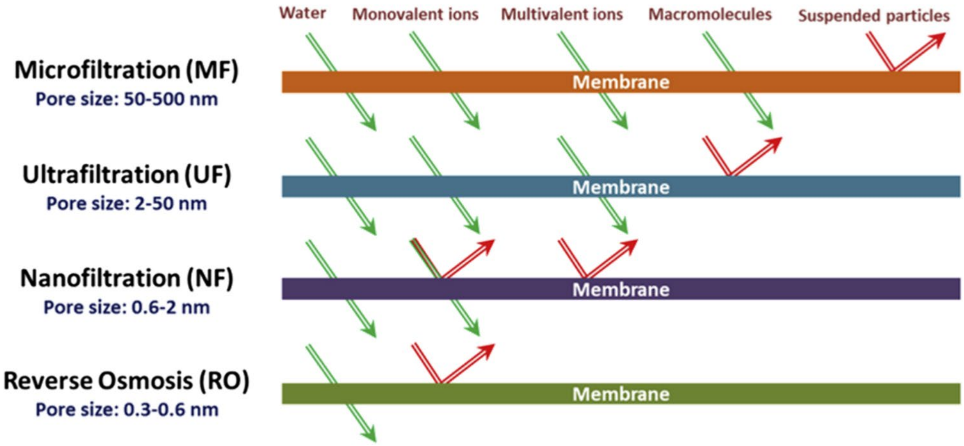


Fig. 3 Schematic diagram of MF, UF, NF, and RO [51]

enables the separation of large molecular weight compounds, such as suspended or colloidal elements, at low-pressure conditions [87, 88]. Microfiltration finds extensive application in wastewater treatment plants globally, demonstrating an impressive efficiency of over 98% in removing organics from water.

Ultrafiltration (UF) is a membrane separation method that operates at a relatively low transmembrane pressure. Its primary objective is to remove dissolved and colloidal particles, such as proteins, polysaccharides, humic material, and various microbiological entities, including viruses [89]. The primary drawback of this pressure-driven process is attributed to the larger pore size. The pore size for UF typically ranges between 2 and 50 nm [81] and MWCO of approximately 1000–100,000 Da [90]. The pore sizes in ultrafiltration are larger than the hydrated forms of metal ions. The typical operating pressure for this process falls within the range of 1–8 bar [91]. Ultrafiltration (UF) finds application in various industries such as the dairy industry, biotechnology, and pharmaceuticals (for tasks like endotoxin removal, antibiotic production, and blood plasma processing) [92]. Additionally, UF is utilized in the food and beverage industry, industrial processes, and wastewater treatment (for tasks like oil removal and addressing dissolved natural organic matter). Moreover, UF serves as a pretreatment method for seawater before undergoing reverse osmosis [93].

Nanofiltration (NF) is the intermediate membrane process between UF and RO. These membranes have a pore size in the 0.6–2-nm range [89]. This separation process usually operates at pressures in the 5–30-bar range [94]. Nanofiltration possesses properties between those of UF and Reverse osmosis (RO), and therefore, the pore size is usually less than 2 nm, corresponding to an MWCO of 100–1000 Da [95]. NF can remove low molecular weight molecules like sugars, amino acids, and divalent ions, while some monovalent ions are still able to permeate through the membrane. NF is used in many industries such as dairy, food and beverage [96], textile, and dyes [97]. Nanofiltration (NF) membranes exhibit an asymmetric configuration and carry a negative charge [95]. This characteristic enables the exclusion of ions through the repulsion of anions from the membrane surface groups. This separation process, particularly effective for multivalent anions, complements the solution-diffusion mechanism underlying reverse osmosis (RO). Consequently, NF membranes can achieve ion rejections comparable to RO membranes while also allowing for higher water fluxes due to their open structure[95]. Nevertheless, the NF performance is much more sensitive than RO due to the ionic strength and pH of source water and it strongly depends on the bulk anion concentration [95].

RO stands out as the most efficient technology for eliminating inorganic contaminants, dissolved salts, and chemical constituents from water. The semi-permeable membrane primarily permits the passage of water while effectively retaining a majority of pollutants. Notably, this technique contributes to over 20% of the global desalination capacity [98]. Membranes are dense with a pore size ranging between 0.3 and 0.6 nm and molecular-weight cut-off about 100 Da [72]. RO finds application in diverse processes, encompassing selective separation, purification, concentration, and desalination. In the food industry, RO is employed for concentrating fruit and vegetable juices, de-alcoholizing alcoholic beverages, pre-concentrating milk or whey, and purifying drinking water [99]. RO is also used in industrial processes (wastewater treatment, desalination of seawater), automotive manufacturing, or the treatment of landfill leachates [100]. One of the main disadvantages is the energy consumption, due to the high pressure needed, usually around 60 bar to overcome the osmotic pressure, affected also by the presence of components in water, such as hardness due to Ca^{2+} and SO_4^{2-} anions [101].

4 Ceramic membranes

Industrial applications have witnessed a rise in the utilization of ceramic membranes, showcasing their ability to rival the performance of polymer membranes while offering distinct advantages in specific scenarios [102]. Ceramic membranes have garnered increased attention due to their potential for reuse, superior resistance to contamination compared to polymer membranes, and the presence of functional properties, such as photocatalysis [71, 103]. This means that ceramic membranes can facilitate the degradation of organic pollutants by activating photocatalytic reactions, thereby enhancing the wastewater treatment process [103, 104]. Polymeric and ceramic materials are widely employed for membrane production.

In the realm of water treatment and desalination, polymeric membranes have emerged as the primary choice in recent times. Nonetheless, these membranes possess certain limitations, including poor long-term stability, susceptibility to fouling, and relatively short lifespans [51]. The unique properties of ceramic membranes, including high porosity, narrow pore size distribution, and superior separation capabilities, have acquired significant interest in the field of water and wastewater treatment [105–107]. As a result, ceramic membranes are increasingly recognized for their potential contributions in this domain. Ceramic membranes are useful for treating wastewater containing corrosive chemicals because of their great chemical and thermal resistance [51]. Ceramic membranes have improved stability and a longer lifetime compared to polymeric membranes [108]. Due to its superior fouling resistance compared to polymeric membranes, it is less likely to clog and may retain its filtration effectiveness for a longer length of time [109, 110]. Despite the numerous advantages that ceramic membranes bring to wastewater treatment, it is crucial to acknowledge their limitations. One notable constraint is their restricted use in full-scale applications, primarily attributable to their high capital cost. Ceramic membranes tend to be more expensive than polymeric membranes due to the requirement of high-temperature sintering and specialized manufacturing techniques [111]. However, the brittleness of these membranes presents a significant obstacle in terms of optimizing module packing density and minimizing the environmental footprint of ceramic membrane-based treatment facilities [112].

4.1 Characterization of ceramic membranes

Ceramic membranes exhibit unique mechanical properties, including high strength, resistance to chemicals, and thermal stability [113, 114]. These aspects perform well for demanding conditions like high-pressure operations and applications involving high temperatures [114]. Ceramic membranes play a crucial role in diverse industrial applications, serving as an essential element in processes such as microfiltration, ultrafiltration, and nanofiltration [115]. This versatile application extends across industries such as textiles, pharmacy, chemicals, and leather, where ceramic membranes play a pivotal role in concentrating or separating compounds from liquids [114]. One of the key properties contributing to the efficiency of ceramic membranes is their high porosity [113]. This feature enables effective filtration and separation of substances. Additionally, these membranes exhibit high permeability, guaranteeing the efficient flow of fluids through the membrane. The defined pore size of ceramic membranes enables for precise control of the filtration process, adding an additional layer of versatility to their application [116]. One notable quality of ceramic membranes is their mechanical robustness, which makes them long-lasting and appropriate for high-pressure applications. Their optimal filtration performance is facilitated by their low surface roughness, which is frequently attained through a mesoporous intermediate layer [117, 118]. The integrated stability of ceramic membranes—which includes mechanical, thermal, and chemical stability—makes them adaptable to a wide range of industrial uses.

4.2 Economic viability of ceramic membranes

Ceramic membranes have various benefits such as high-temperature stability, fouling resistance, and low maintenance requirements, making them a principle for water treatment applications [104, 119]. However, the high production cost of ceramic membranes has been a significant challenge, restricting their large-scale production and application [104, 120]. The high cost of ceramic membranes is due to the expensive raw materials, high energy use, and complex preparation processes [120, 121]. Addressing this concern is of utmost importance to facilitate the widespread adoption and acceptance of ceramic membranes across diverse applications [121]. Metawater, a Japanese company, showcased the application of ceramic membranes in diverse settings [122]. Ceramic membranes have been used for water reclamation, demonstrating comparable performance to polymeric membranes but with higher capital costs. However, ceramic membranes offer cost savings in terms of operating and maintenance expenses, as well as a longer lifespan compared to polymeric membranes, although membrane replacement is required when fouling occurs [119]. Based on a cost analysis, a comparison between ceramic and polymeric membranes for water treatment plants (WTPs) showed that their life-cycle costs are comparable, with ceramic membranes costing around 0.28 USD per cubic meter and polymeric membranes costing around 0.27 USD per cubic meter [123]. Another study conducted a techno-economic analysis and found that ceramic membranes made of alumina and polymeric membranes made of polyethersulfone (PES) have similar performance in terms of cost [122]. While the initial cost of alumina ceramic membranes is higher, considering factors such as membrane lifespan and labor requirements, they become a cost competitive option [124]. Techno-economic analyses have also shown that ceramic membrane plants have comparable costs to polymeric plants, with membrane replacement being a significant cost-saving factor [122].

4.3 Composition and structure

Ceramic membranes predominantly consist of alumina, silica, titania, or zirconia [125]. The present studies primarily concentrate on ceramic supports, particularly Al_2O_3 and ZrO_2, chosen for their robust chemical, thermal, and mechanical durability, cost-effectiveness, and resilience against corrosive substances [4]. Ceramic membranes used in water and wastewater treatment have asymmetrical structures [85, 102, 126–129]. The distinct asymmetric configuration is achieved by placing progressively smaller particles and employing elevated sintering temperatures to create continuous and permeable layers [127]. It compromises a thin selective layer, an intermediate layer, and a permeable supporting layer as shown in Fig. 4 [122]. The intermediate and support layers contribute to selectivity, stability, and strength, while the thin selective layer's main function is to facilitate separation [130]. The support layers can vary in terms of density, openings, and porosity. They can be composed of the same material (integral membrane) or different materials (composite membrane), chosen based on the intended molecular weight cut-off [130, 131]. As depicted in Fig. 5, the arrangement and shapes of these membranes are shaped by the supports, resulting in cylindrical, planar geometries, or hollow-fiber membranes with diverse packing densities [24, 132, 133]. Ceramic membranes in tabular and hollow-fiber forms are especially suitable for wastewater treatment due to their enhanced mechanical robustness and compactness [134]. When compared to flat-sheet ceramic membranes, they also show superior handling qualities against high crossflow velocities [4, 109, 134]. However, they can withstand high-turbidity feeds and are simple to replace when packaged in modules [134]. These mechanically adaptable flat sheet membranes can tolerate backwashing, air scrubbing, and high-pressure water jet cleaning [102]. Conversely, cylindrical membranes are more appropriate for the separation of feeds containing high levels of turbidity and a significant quantity of suspended solids

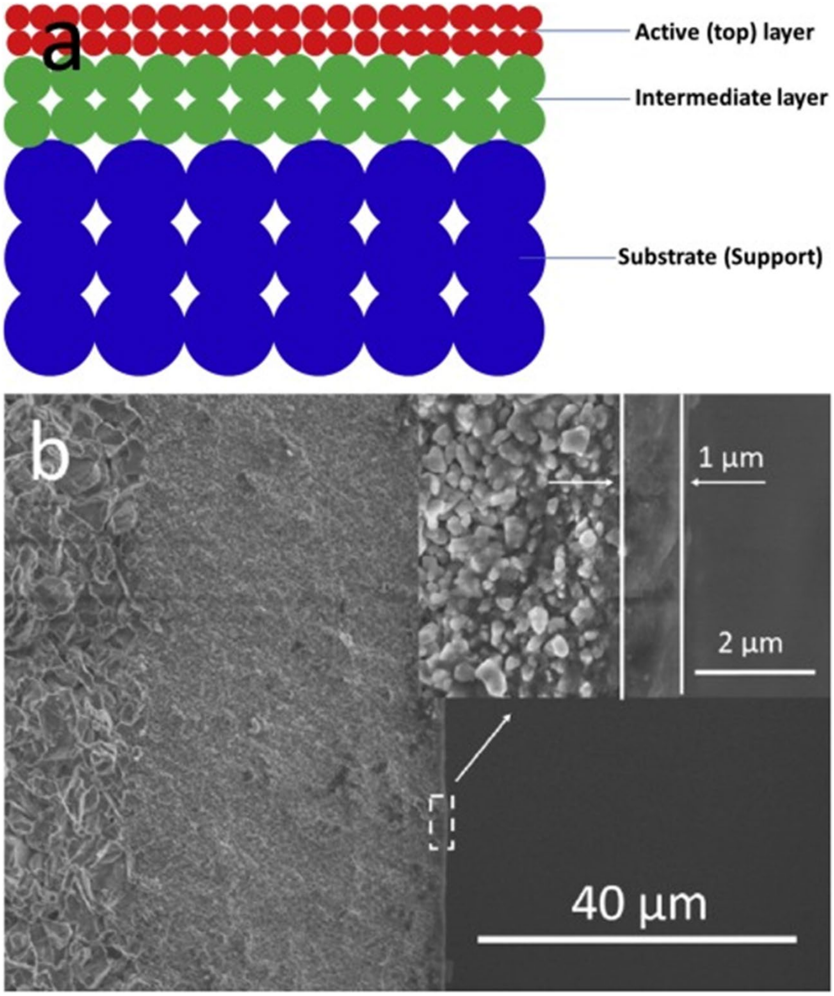


Fig. 4 Microstructure of ceramic membrane in water and wastewater treatment. **a** Schematic diagram and **b** SEM image of cross section of alumina membrane [108]

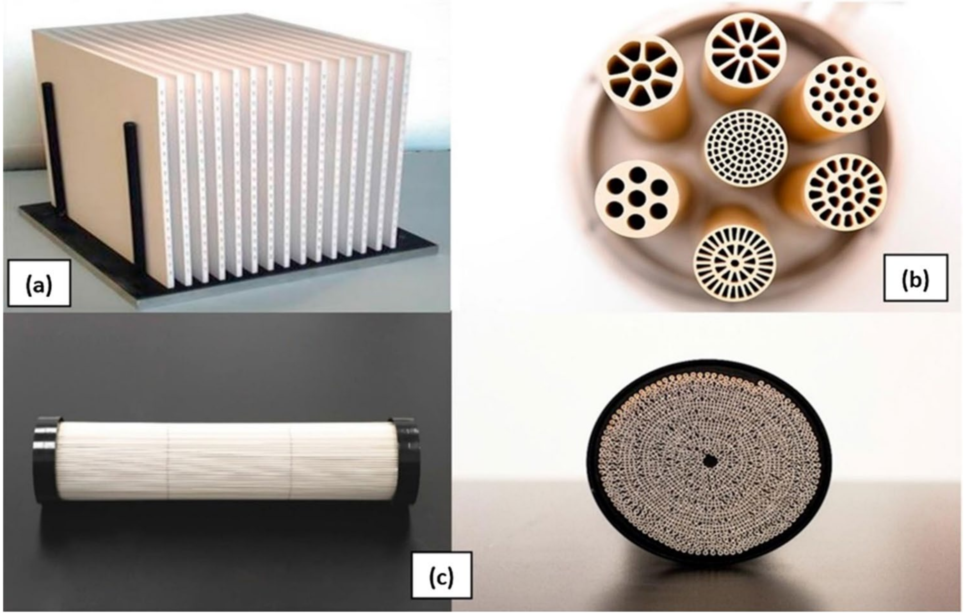


Fig. 5 Geometry of commercially available ceramic membranes. **a** Flat-sheet membrane **b** tubular ceramic membranes, **c** ceramic hollow-fiber membrane [132]

[135]. Because of their greater diameters and durability, they are simpler to cleanse through mechanical means and can proficiently manage fouling even under elevated crossflow velocities [132].

4.4 Ceramic membranes materials

Various ceramic membranes employed in water and wastewater treatment include alumina, zirconia, titania, silica, and zeolite [136, 137]. The selection of a specific material for the ceramic membrane is a deliberate process, taking into account its distinct physical and chemical properties, such as hydrophilicity, microstructure, chemical and thermal stabilities, as well as mechanical strength [138]. Alumina specializes in microfiltration and ultrafiltration, showcasing impressive resistance to fouling and enduring flow rates [137]. Zirconia stands out due to its high hydrophilicity and thermal endurance [139–141]. Titania's proficiency in photocatalysis is invaluable for breaking down pollutants under sunlight [142]. Silica, known for nanofiltration, selectively sieves ions and molecules, leveraging its notable permeability as illustrated in Fig. 6 [143]. Conversely,

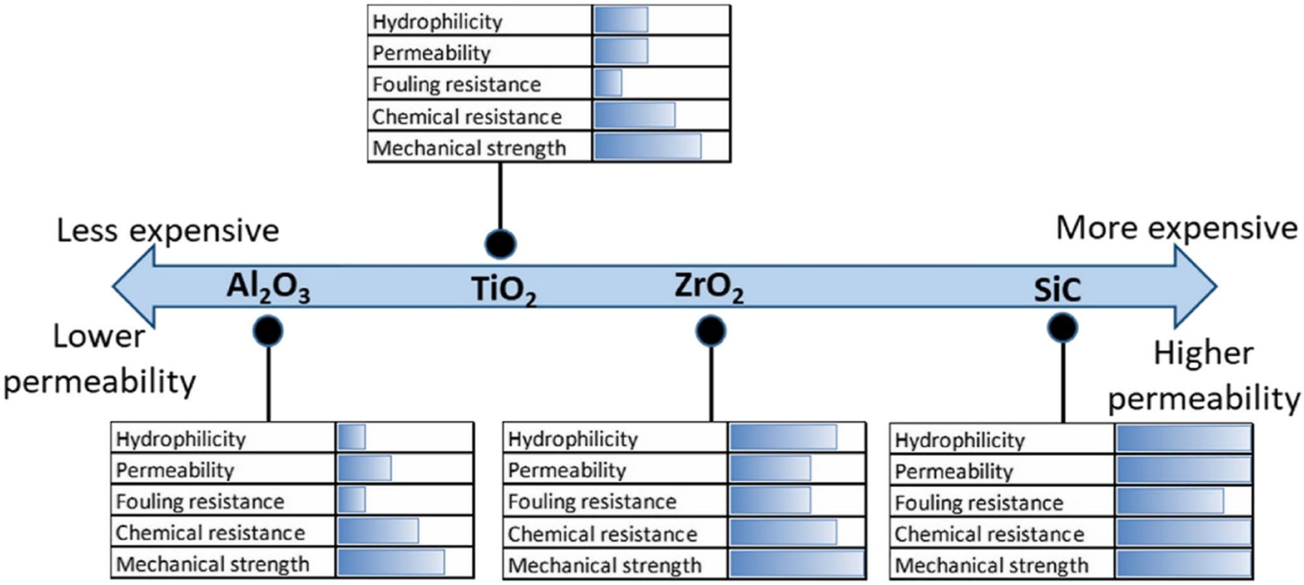


Fig. 6 Properties of commercially available ceramic materials [145]

zeolite's exceptional adsorption and molecular sieving capabilities find applications in various separation processes [144]. Together, these materials cater to diverse treatment demands, contributing to cleaner water resources and more sustainable wastewater management. Ongoing considerations include fabrication intricacy, cost-effectiveness, and operational challenges.

4.4.1 Alumina membrane

The prevalent ceramic material utilized in membrane production is alumina (Al_2O_3). This preference arises from its simple processing and inherent qualities, such as excellent chemical and thermal stability, as well as high strength [146]. Alumina can serve as a substrate, intermediate layer, and an active layer within the ceramic membrane [147–151]. Depending on the specific range of pore sizes, alumina membranes find application in microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) [108]. Alumina membranes, composed of aluminum oxide (Al_2O_3), are widely employed in the purification of polluted water. In an earlier investigation, the application of alumina UF membranes in the remediation of dye-contaminated wastewater was documented [149]. Bilayer α-alumina membranes were created employing a co-sintering procedure that involved precise control of the doping proportions within boehmite sols and alumina. This method led to the development of membranes with elevated performance levels [149]. Although alumina membranes offer benefits such as remarkable mechanical and chemical durability, they encounter obstacles related to costly production, the demand for enhanced permeability and selectivity performance, and the innate brittleness that complicates manufacturing and transport [137]. Furthermore, the issue of membrane fouling is of notable concern, given that pollutants have the potential to accumulate and obstruct membrane pores, resulting in a decline in filtration efficiency [152]. Alumina can take on different phases, commonly referred to as "transition alumina phases," which include gamma (γ), delta (δ), theta (θ), eta (η), and kappa (κ), alongside the thermodynamically stable alpha (α) phase [153]. Despite having these various phases, the alpha phase is mainly preferred for practical uses. The decision to use the alpha phase in alumina is based on its stability and reliability from a thermodynamic standpoint. This phase provides consistent and predictable material properties, ensuring a reliable performance across various membrane applications [154]. While other transition alumina phases may have distinct characteristics, their unstable nature and potential phase changes could introduce uncertainties in membrane behavior [155]. This makes the alpha phase the favored option for achieving the desired and consistent membrane performance.

4.4.2 Zirconia membrane

Zirconia, commonly used in water and wastewater treatment membranes, exhibits three crystal phases—cubic, tetragonal, and monoclinic—within specific temperature ranges under normal air conditions, as depicted in Fig. 7 [102, 156, 157]. The monoclinic phase remains stable up to 1100 °C, the tetragonal phase persists in the 1100–2370 °C range, and the cubic phase is present at temperatures exceeding 2370 °C [141, 156]. Zirconia's outstanding feature is its exceptional hydrophilicity, resulting in high water flow rates and minimal fouling during water treatment [71]. Moreover, its high resistance to heat makes it suitable for liquid-phase applications under demanding conditions. As a result of these advantageous properties, zirconia is extensively employed as the top active layer in MF, UF, and NF processes for water and wastewater treatment [141]. One of the primary uses of zirconia membranes is acknowledged to be wastewater treatment. Zirconia membranes have demonstrated superior efficacy compared to alumina membranes for wastewater treatment, especially when it comes to oil–water separation for instance [102]. In a prior investigation, symmetric and asymmetric tubular zirconia membranes produced on alumina supports both showed high permeance [141]. When compared to alumina membranes, the zirconia membrane performed better in terms of a greater and more steady flux as well as less fouling [158]. Zirconia membranes have

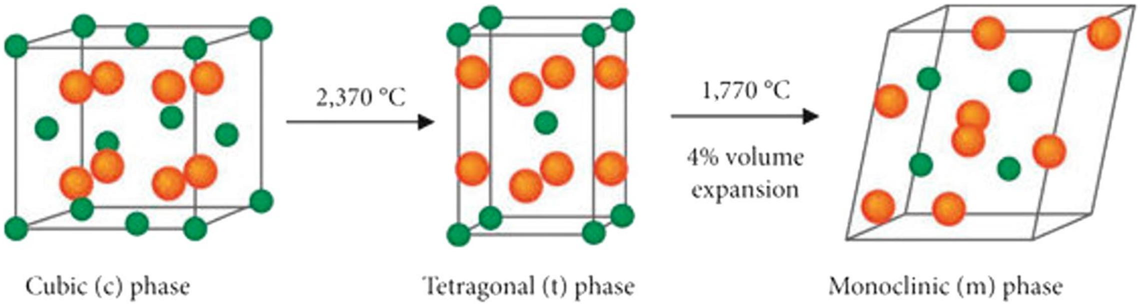


Fig. 7 Zirconia phase transformation [158]

significant applications in wastewater treatment, particularly in oil–water separation. Compared to alumina membranes, zirconia membranes exhibit higher flux, lower fouling, and better oil rejection. In a study [159], tubular zirconia membranes achieved very high permeance, around 400 and 1500 l/(m^{2}h bar), on symmetric and asymmetric supports, respectively, demonstrating superior performance in oil–water separation due to their higher and more stable flux and reduced fouling.

4.4.3 Titania membrane

Within its composition, titania (TiO_2) consists of three minerals: rutile, anatase, and brookite [102]. Among various ceramic materials, titania exhibits the highest level of chemical resistance [139]. In water and wastewater treatment, it serves as a support in the intermediate and active layers for processes like UF and NF, leveraging its photocatalytic properties [160, 161]. The inclusion of titania in the membrane imparts multifunctional capabilities to the water treatment process. Specifically, it proves effective in treating water containing corrosive elements, as it demonstrates remarkable chemical stability compared to other ceramic materials [139]. Titania (titanium dioxide) has been used in the treatment of water and wastewater as an active layer, intermediate layer, and support for UF and NF membranes [160, 162–165]. These titania membranes' distinctive photocatalytic qualities enable their multipurpose use in the treatment of water. For instance, titania nanowire UF membranes with layered hierarchical structures were created in a prior study and demonstrated good permeability as well as antifouling and antibacterial characteristics [142]. A study investigated the structure and performance of titania membranes (TM) produced using different vacuum exposure times for molecular weight cut-off and oil/water separation [166]. The membranes were synthesized using the sol–gel method and coated on macroporous alumina tubes, followed by exposure to varying vacuum times and calcination. The results showed that the size of titania particles increased with longer vacuum exposure, and the TM membranes had an average pore diameter of approximately 3.6 nm [166]. The membranes were effective in rejecting larger molecules but were unable to separate glucose and sucrose, indicating that the pore sizes were larger than the kinetic diameter of sucrose. Additionally, the water flux of the membrane decreases as the molecular weight of the tested substances increases, indicating the effectiveness of nanofiltration.

4.4.4 Silica membrane

Silica (SiO_2) membranes have been developed for water and wastewater treatment [167]. These membranes have the ability to control pore sizes, allowing them to purify water through desalination [71]. However, one drawback of silica membranes is their unstable structure when in contact with water, which requires improvement in their hydrostability [168]. Researchers have explored various strategies such as carbonized templating [169], hybrid organosilica [170] development, and metal doping [170] to modify the surface properties of silica membranes, aiming to enhance their hydrostability. Furthermore, they harnessed the potential of sol–gel techniques to substantially diminish the presence of silanol groups. This strategy yielded enhanced hydrostability and exceptional efficacy in desalination for the silica membrane, distinguishing it from alternative silica-based membranes [168].

Hollow fiber ceramic membranes are known for their unique properties, such as thermal, chemical, and mechanical stabilities. However, their high cost of raw materials hinders their commercialization. Researchers developed a low-cost silica sand-based hollow fiber ceramic membrane (SS-HFCM) using a combined phase inversion/sintering technique as illustrated in Fig. 8 [171]. The fabricated SS-HFCM exhibited satisfactory morphological structure, mechanical strength, and enhanced oil–water separation performance, making it suitable for various water treatment applications. This study successfully produced a ceramic membrane called HFCM using low-cost silica sand through phase inversion/sintering. The evaluation of the fabricated membrane showed that an optimal configuration of the HFCM can be achieved with 55 wt% silica sand content, sintered at 1300 °C, a bore fluid flow rate of 10 mL/min, and a suspension extrusion rate of 6 mL/min [171]. The fabricated membranes demonstrated promising potential for various applications in oil–water separation and wastewater treatment. The findings suggest that silica sand has potential applications in water treatment processes, including industrial seawater desalination.

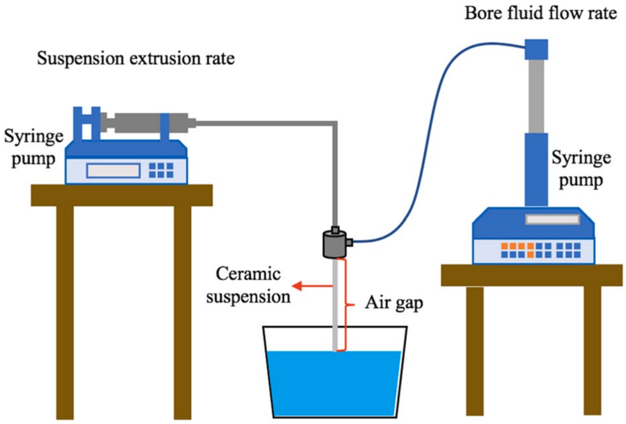


Fig. 8 Phase inversion extrusion diagram [171]

4.4.5 Zeolite membrane

Zeolites are aluminosilicates with a crystalline structure and hydrated state, containing cations. These membranes possess distinctive pore structures, comprising uniform subnanometer zeolitic pores and inter-crystal micropores with a specific size distribution [172]. As a result, water is anticipated to be transported through both the inter-particle and intra-particle pores. Moreover, their inherent hydrophilicity aids in mitigating fouling [173]. Zeolite membranes find applications in water and wastewater treatment and can be utilized for desalination through microfiltration (MF), ultrafiltration (UF), and reverse osmosis (RO) processes [108]. Zeolite membranes have promising potential for desalination of complex mixtures, as demonstrated by their high rejection rate in RO of concentrated solutions with different cations [174]. However, achieving defect-free zeolite membranes with the desired thickness remains a challenge.

The exceptional ion-exchange characteristics of natural zeolite make it highly promising for utilization as an adsorptive ceramic membrane designed for the removal of ammonia from water [175]. In a study, the successful production of an adsorptive ceramic membrane using natural zeolite has been achieved through the implementation of phase inversion and sintering techniques [176]. The response surface methodology (RSM) approach was applied to identify the optimal conditions, specifically the feed pH, initial feed concentration, and dosage of the adsorptive membrane, aiming to enhance both membrane water permeability and ammonia removal efficiency [175]. This method proves particularly advantageous when numerous factors impact the yield, production, or removal efficiency within a given process or system. The experimental phase involved creating an adsorptive hollow fiber ceramic membrane (HFCM) from clinoptilolite (a natural zeolite) through a combination of phase inversion and sintering techniques [175]. The membrane's ability to remove ammonia was assessed using a crossflow membrane setup. Subsequently, the effectiveness of the adsorptive HFCM was examined through a designed experiment using RSM to assess the relevant influencing factors. The study successfully fabricated and utilized a hollow fiber ceramic membrane (HFCM) for ammonia removal in water. The results indicated that under optimal conditions (feed pH of 7.04, feed concentration of 75 mg/L, and HFCM dosage of 0.35 g), high levels of water permeability and ammonia removal were achieved with small average errors in confirmatory tests [175]. HFCM demonstrated excellent ammonia removal performance of 96.5%, indicating its potential as a synergized system for water adsorption and filtration and showed an effective ammonia uptake due to the compact alignment of natural zeolite particles within its structure. Overall, these findings suggest that the developed adsorptive HFCMs have great potential for use in synergized systems combining water adsorption and filtration processes for efficient ammonia removal from contaminated water sources. As illustrated in Fig. 9, the correlation analysis shows that the optimal ammonia removal occurs at pH 7.50 with a median concentration of the ammonia feed solution. The adsorption of ammonia is more favorable at neutral pH due to the high negative charge on the surface of the adsorbent (HFCM) and the intensified adsorption competitiveness between H + ions and ammonia at lower pH.

4.5 Advantages and limitation of ceramic membranes

Ceramic membranes have garnered significant attention in separation techniques owing to their exceptional attributes, although their real-world application is influenced by both unique benefits and intrinsic restrictions. Ceramic membranes, in general, exhibit excellent chemical stability and can withstand exposure to acids, alkalis, and organic solvents, while also demonstrating resistance to oxidation [122]. As a result, they may provide consistent performance throughout a lengthy service life, which has been demonstrated in several industrial installations [177]. They possess a high mechanical strength, remaining undamaged even under high-pressure conditions [178]. They have a great mechanical strength and can withstand tremendous pressure without breaking [179]. Their pore size distribution is narrow and precise, which results in a separation efficiency that is noticeably high, enabling for the efficient removal of particles like virus pathogens in drinking water or emulsified oils in wastewaters [180]. Additionally, ceramic membranes have a high degree of material stability in abrasive environments, allowing for the efficient removal of suspended or dissolved solids from industrial solvents. Additionally, they can be cleaned with abrasive chemicals to maintain membrane performance stability, which is essential for dealing with waste streams that are prone to fouling [181, 182].

These ceramic membranes do, however, have some drawbacks. Due to their fragility and vulnerability to mechanical stress, handling and operation may compromise their structural integrity, necessitating cautious installation and maintenance methods [109, 112, 182, 183]. The manufacturing complexity of these membranes often leads to higher production costs compared to polymeric alternatives [184]. Recent developments have solved the difficulties of cost and packing density, putting ceramic membranes on scale with polymeric membranes and increasing their acceptance in a variety of applications. Their relatively low porosity and permeability might necessitate higher operating pressures, consequently increasing energy consumption [185]. Additionally, the narrow pore size distribution can constrain their suitability for certain separation tasks, potentially limiting their versatility [186, 187]. In addressing these challenges,

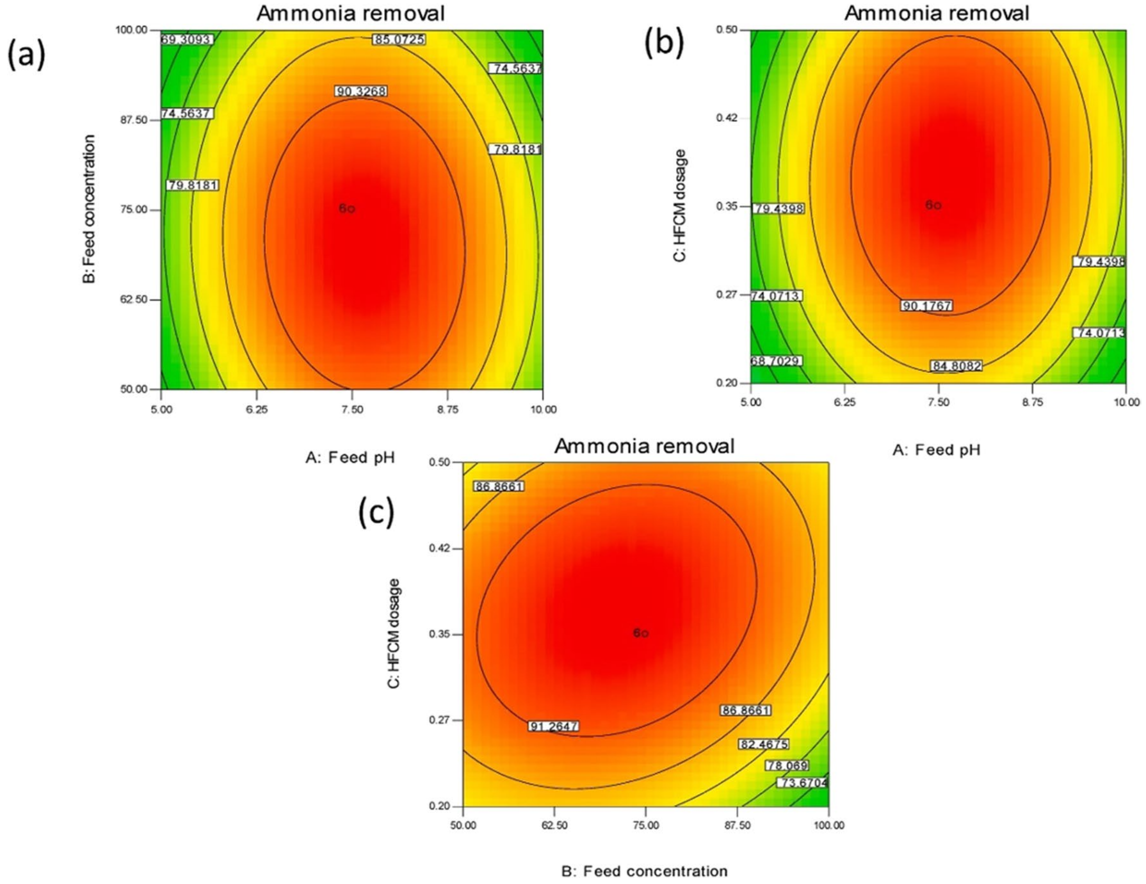


Fig. 9 Ammonia removal by adsorptive HFCM 3D plot, (**a**) The interaction between the feed pH and feed concentration, (**b**) The interaction between the feed pH and HFCM dosage, (**c**) The interaction between the feed concentration and HFCM dosage [175]

ongoing research is focused on refining fabrication techniques, optimizing pore structures, and exploring hybrid membrane designs to harness the full potential of ceramic membranes in various industrial applications. Another main limitation of ceramic membranes that have concerned researchers is membrane fouling, which greatly lowers its effectiveness. This is caused by organics, inorganic substances, and microorganisms clogging the pores and polluting the membrane surface [102].

4.6 Membrane fouling

Membrane fouling occurs when a liquid solution containing different pollutants passes through a ceramic membrane; the pollutants can accumulate either in the pores of the membrane or on its surface due to various physical and chemical effects [110, 112, 188, 189]. To ensure the efficient and stable operation of ceramic membranes for water treatment, it is crucial to control membrane fouling. Addressing membrane fouling requires understanding its formation and underlying drivers. As shown in Fig. 10, the accumulation of pollutants leads to membrane fouling, which can be classified into different mechanisms such as complete blocking (when pollutants are larger than the pores), standard blocking (when pollutants are smaller and accumulate through adsorption), and intermediate blocking (when only some pores are sealed) [109, 112, 188, 190]. Fouling often arises from the physical and chemical interactions of particles, colloidal particles, or large solute molecules present in the feed liquid that come into contact with the membrane [191]. Moreover, the fouling rate is directly influenced by the hydrophobic nature, electrical charge, and pore dimensions of the membrane, as exemplified by hydrophilic membranes such as alumina membranes [112, 192]. A comprehensive understanding of these membrane characteristics enables the development of effective strategies to mitigate fouling, thereby ensuring the optimal performance of ceramic membranes in water treatment applications [122].

As summarized in Fig. 11, fouling mitigation methods include pretreatment techniques (such as filtration, water softening, and acidification) to minimize fouling formation, as well as cleaning methods (such as flushing, backwashing, and air bubbling) to remove foulants from the membrane surface [110, 189, 194–196]. Pretreatment methods are more suitable for inorganic fouling, while cleaning methods are effective for removing organic fouling [197]. Pretreatment

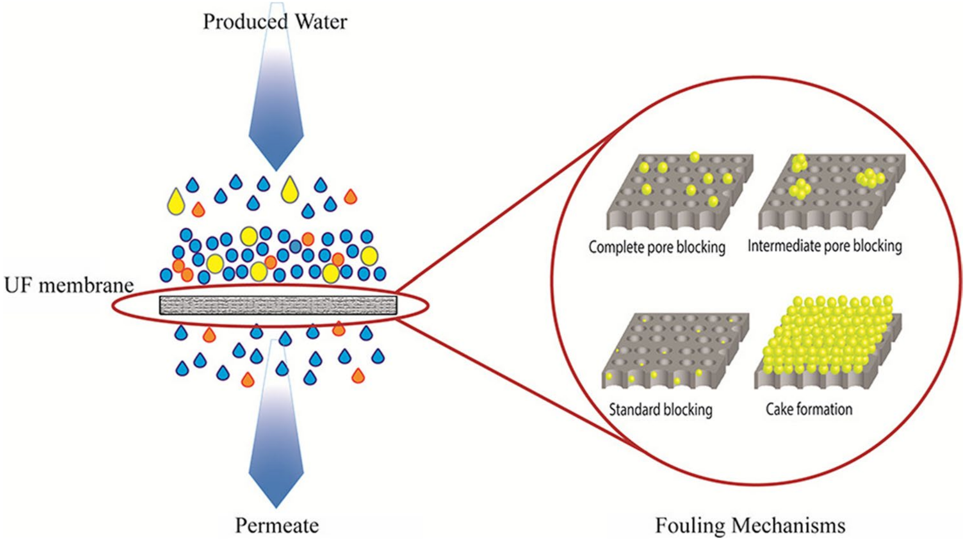


Fig. 10 Ceramic membrane fouling mechanism [193]

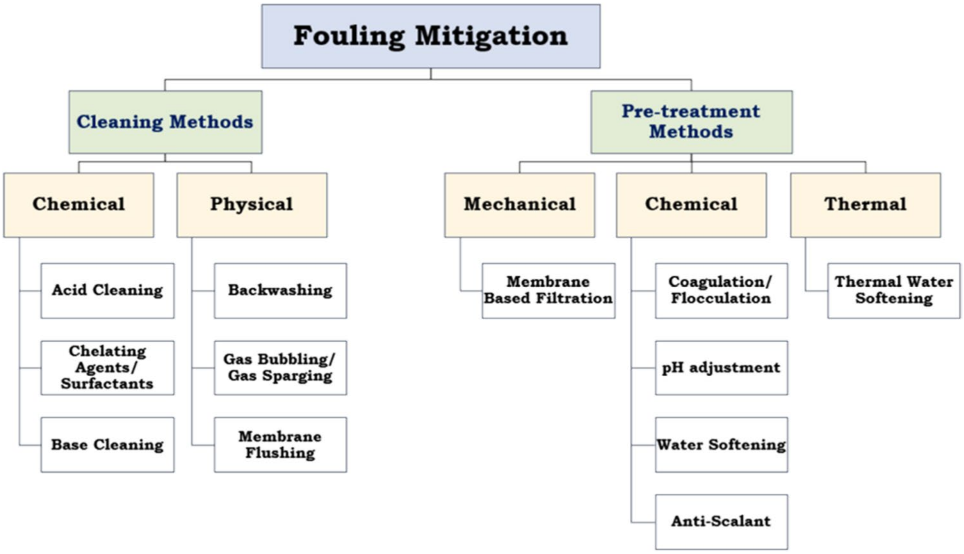


Fig. 11 Fouling mitigation strategies [110]

methods are used in membrane-based processes to prevent fouling. These methods employ various strategies to minimize the presence of foulants in the feed solution, reducing the likelihood of fouling. While pretreatment is more crucial in pressure-driven treatment processes, it has been proven effective in membrane distillation (MD) as well, playing a vital role in reducing fouling, improving water quality, enhancing MD performance, and extending membrane lifespan, particularly when dealing with real feed water containing a mixture of different foulants. Pretreatment methods, such as coagulation/flocculation, water softening, anti-scaling, membrane filtration, thermal water softening, and pH adjustment, can be categorized into mechanical, chemical, or thermal methods, or a combination of these [110, 198–201]. On the other hand, membrane cleaning methods serve not only to remove accumulated particles from the membrane surface but also to restore the membrane's original condition [110, 196]. Cleaning methods can be categorized into two ways both chemical and physical [110, 202]. Membrane surface fouling is removed physically through membrane filtration by applying hydraulic and mechanical forces [203]. Additionally, chemical cleaning methods involve the use of various chemical agents such as acids, alkalis, oxidants, enzymes, and surfactants [204]. By lowering the cohesive forces between the membrane surface and the contaminants, these agents facilitate the removal of the contaminants [205].

4.6.1 Causes of membrane fouling

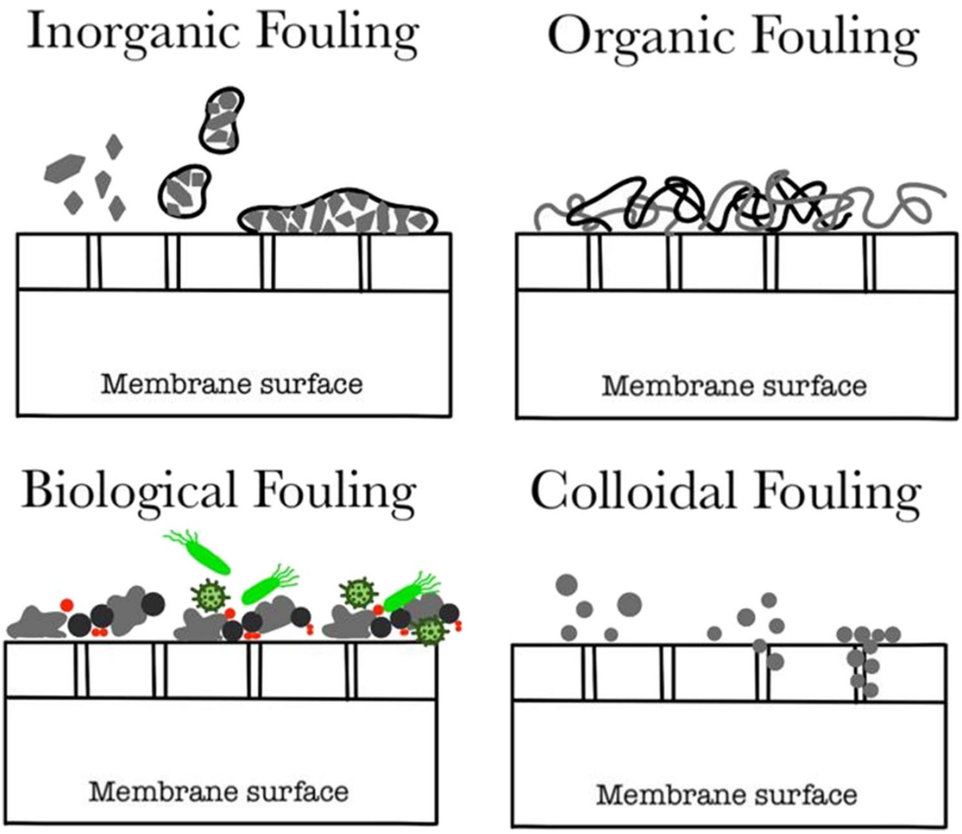
In nearly all membrane processes, membrane fouling results from the precipitation and deposition of molecules or particles on the membrane surface or pores [181].

Particulate fouling is a significant contributor, wherein suspended solids, colloids, or fine particles in the feed water deposit on the membrane surface, leading to fouling [206]. These particles may vary in size and can be organic or inorganic in nature [207]. Another contributing factor is scaling, which occurs when dissolved inorganic salts like calcium carbonate, calcium sulfate, or silica exceed their solubility limits and form deposits on the membrane surface [181, 208]. Scaling is often influenced by the concentration and pH of the feed water [209]. Moreover, organic compounds such as oils, greases, proteins, carbohydrates, and humic substances can accumulate both on the membrane surface and within its pores [110, 210]. These organic foulants may originate from sources like wastewater, food processing, or natural organic matter present in water sources [211]. The reduction in the hydrophobicity of the membrane material over time and due to membrane damage is an additional factor that expedites the fouling of the membrane [110]. The degree of hydrophilicity or hydrophobicity in a membrane is established through the contact angle θ, wherein a greater angle signifies a surface with higher hydrophobicity [212]. This property has a substantial impact on the membrane's resistance to fouling and is determined by the surface shape and pore size of the membrane [213]. Compared to hydrophobic membranes, hydrophilic membranes are less prone to adsorption, have faster flow rates, and have better anti-fouling capabilities [214].

4.6.2 Types of membrane fouling

The types of membrane fouling fall under four categories: inorganic fouling, organic fouling, biological fouling, and colloidal fouling, as illustrated in Fig. 12 [110]. Inorganic fouling is the accumulation of solid inorganic compounds like calcium carbonate or calcium sulfate [110]. These inorganic components come from the feed solution and undergo scale formation through complex mechanisms of crystallization and transport processes [194]. Organic fouling is caused by the accumulation and deposition of relatively dense organic materials, such as polysaccharides, proteins, humic substances, nucleic acids, lipids, and amino acids [189]. Dissolved organic matter (DOM) is abundant in both surface water and wastewater and can be classified into natural organic matter (NOM), synthetic compounds, and soluble microbial products (SMPs) [191]. NOM consists of various substances such as humic acid, carbohydrates, proteins, lipids, and low molecular weight species [215]. These NOMs can exist as dissolved particles or colloidal materials and can attach to the membrane surface through mechanisms like hydrophobic interactions, chemical affinity, and electrostatic forces [191]. Biological fouling, also

Fig. 12 Types of membrane fouling



known as biofouling, occurs when bacteria or microorganisms multiply and accumulate on the surface of a membrane [216]. This biofilm formation reduces the permeability of the membrane, leading to decreased productivity and long-term operational issues [217]. Colloids are small, suspended particles that can cause fouling in water solutions—they range in size from nanometers to micrometers and can lead to significant fouling issues [218, 219]. In the context of water treatment, colloidal fouling is classified as either inorganic or organic, with inorganic colloids like silica, aluminum silicate minerals, clay, silt, iron oxides/hydroxides, and debris being the predominant culprits found in natural water sources [220, 221].

4.6.3 Correlation between pore size and fouling

The membrane's surface characteristics and the relative size of its pores are critical factors influencing fouling mechanisms and severity [220]. If the pore size is significantly larger than the particles or substances to be removed, fouling may occur as contaminants can easily pass through and accumulate downstream [181, 212]. Conversely, excessively small pore sizes can lead to clogging or fouling due to particle build-up on the surface or within the pores, restricting flow and decreasing filtration efficiency [222]. Nevertheless, in certain cases, smaller pore sizes can mitigate fouling by physically preventing larger particles or microorganisms from passing through the filter [212, 223]. Furthermore, smaller pores can create more convoluted paths for fluid flow, increasing the likelihood of particle collision and removal [204]. Nonetheless, smaller pore sizes might also be more vulnerable to fouling caused by smaller contaminants adhering to the pore walls [224]. It was discovered in a treatment study of wastewater containing micropollutants [225] that the membrane's pore size is the primary factor impacting the membrane flux and the wastewater's rate of turbidity reduction [180]. Greater membrane pore size leads to increased membrane fouling, resulting in accelerated flux decay and a decrease in the removal rate [212, 226]. The performance of the membrane for separation is significantly impacted by the size of the membrane pores.

5 Mechanism of ceramic membrane

5.1 Fabrication of ceramic membrane

The exact handling of ceramic powders, binders, shaping methods, and controlled heat treatment are all necessary for the manufacture of ceramic membranes [227]. These membranes, which are known for their dependability, chemical resistance, and effectiveness, are used in a variety of processes, including fuel cells, nanofiltration, gas separation, and water purification [228]. Publishing research findings on the preparation of ceramic membranes is imperative as it contributes to the scientific knowledge, as depicted in Fig. 13, which illustrates the trend in publications over the past decade concerning the preparation of ceramic membranes. As depicted in Fig. 14, choosing ceramic powders with the necessary membrane qualities in mind is the first step in the production of ceramic membranes [126]. Powders are combined with binders to create a paste, and it is essential to maintain the appropriate binder-to-powder ratio to ensure effective cohesion during shaping and handling processes [229]. Additionally, additives may be included to enhance properties like pore structure or mechanical strength. There are many methods for creating a single layer or multilayer ceramic membrane for the shaping method, including slip casting, extrusion, pressing, phase inversion, and sol–gel [71, 230–232]. The drying process then removes

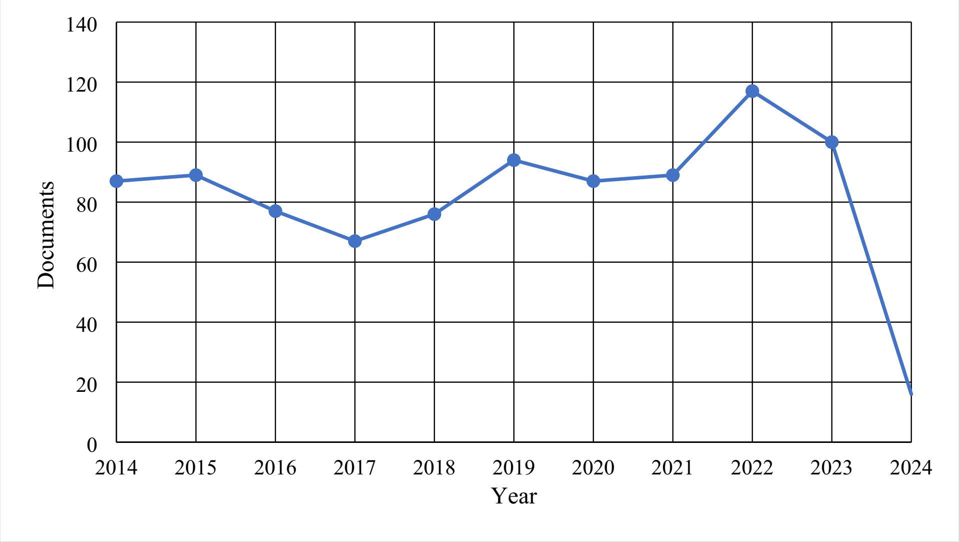


Fig. 13 Number of publications in 10 years on the preparation of ceramic membranes

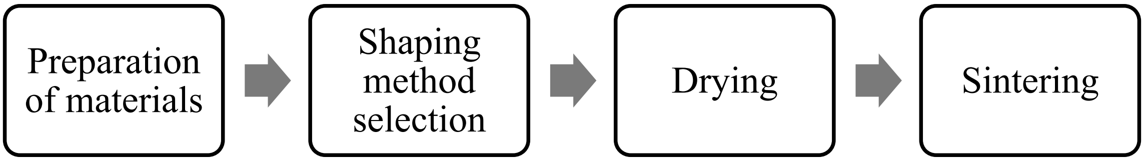


Fig. 14 Flowchart for the preparation of a single layer of ceramic membrane

the solvent from the binder, and it must be controlled to prevent cracks or deformations. Sintering involves heating the membrane at high temperatures [233]. It is a critical step for densification and pore structure development. The sintering temperature and time are carefully controlled to achieve the desired membrane characteristics. The process removes residual organics and promotes particle bonding [234].

5.1.1 Slip casting method

The slip casting process begins by pouring a slurry onto a microporous mold made of plaster of Paris (POP) [126]. The mold's porous nature creates capillary suction pressure, which draws the fluid from the slurry into the mold. As a result, a consolidated layer of solid (cast) forms on the mold's walls. The mixing of particle suspension and pouring it into a porous mold allow solvents to diffuse through the pores and form a particle layer on the mold's internal surface [235]. Once the desired cast thickness is achieved, any excess slip is poured out, and the mold and cast are left to dry as illustrated in Fig. 15 [236]. During drying, the cast undergoes contraction from the mold and can be easily detached. Once completely dried, the cast is heated to eliminate the binder and then sintered to yield the final product [230]. This technique has been utilized to produce ceramic membranes using economical resources such as kaolin [237] and fly ash [238], yielding membranes with exceptional permeation characteristics and reduced pore dimensions. For example, a porous tubular ceramic membrane constructed from mineral coal fly ash displayed a uniform surface, an approximate average pore size of 0.25 mm, and a hydraulic permeability of 475 L/(h m^2 bar), making it suitable for the treatment of dyes in wastewater originating from the textile sector [235].

5.1.2 Extrusion method

This technique has made considerable progress in recent years and has found widespread use in the molding of ceramic items, particularly in the creation of single-channel and multichannel supports [240]. Extrusion entails stirring as powder is combined with plasticizers, binders, and other ceramic additives. The mixture then undergoes a number of procedures, including vacuum pugging and aging, before being pushed under pressure (20–180 MPa) into the die nozzle to extrude the support into the desired shape [241]. The shaping method of the paste in the production of ceramic membranes depends on the geometry of the final membrane support. Figure 16 illustrates how the extrusion method's preparation stages for a ceramic membrane support may often be broken down into six steps: mixing, vacuum puddling, aging, extruding, straightening, drying, and sintering

Fig. 15 Schematic diagram of the slip casting process [239]

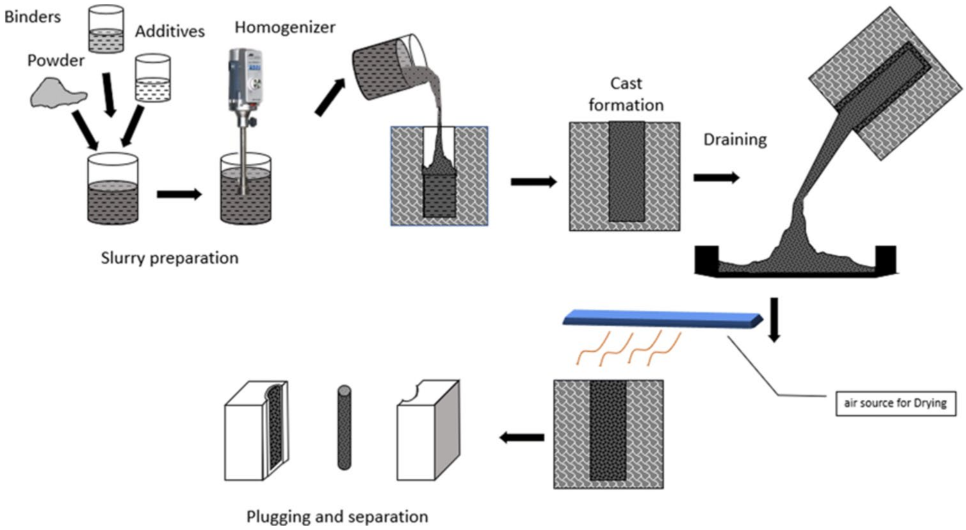
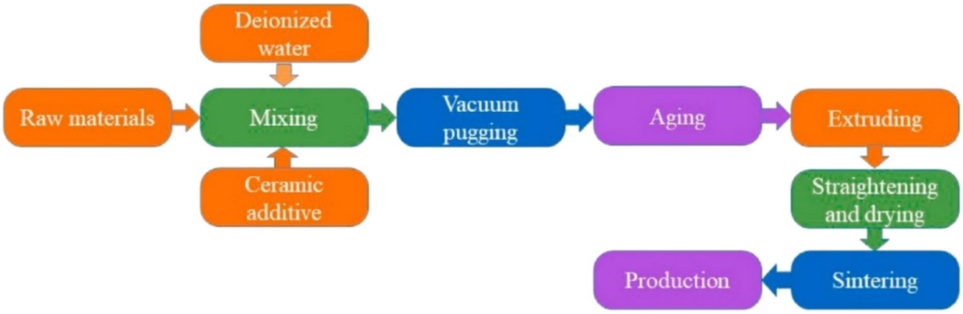


Fig. 16 Extrusion method process [240]



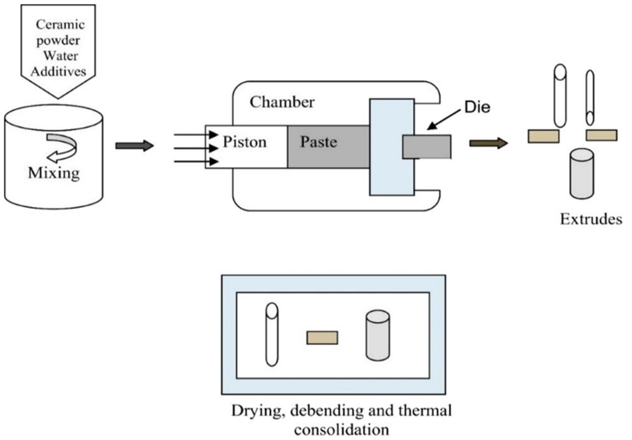


Fig. 17 Extrusion method illustration [235]

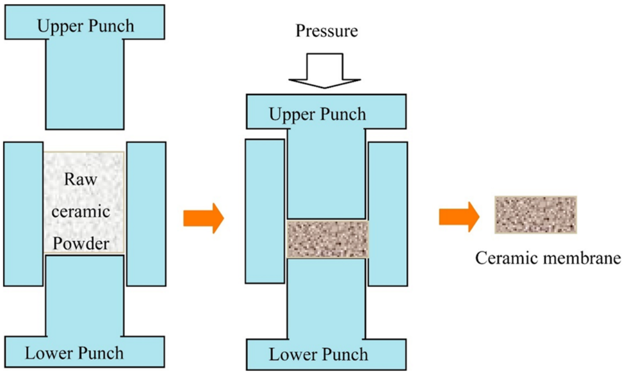


Fig. 18 Pressing method process [235]

[242]. This process is achieved by pushing the mixture through a nozzle using either a screw extruder or a piston extruder [231]. The piston extruder, consisting of a piston, tube, and die, as shown in Fig. 17, is known for its ease of use [235]. It is crucial for this extruder to ensure a homogeneous mixture of the powder and other additives while generating sufficient pressure to transfer the mixture to the die [240]. It involves a continuous deformation process where the paste is forced through a smaller die opening using the piston press. This process determines the shape, pore size distribution, and porosity of the final ceramic membrane product. The raw ceramic membranes are then dried at room temperature and treated under high-temperature conditions to avoid crack formation before reaching the sintering temperature of the material. This particular method is chosen due to its ability to create a robust membrane structure. Yet, it involves a complex preparation process and requires the application of adequate pressure to facilitate the movement of the mixture [243]. Compared to other methods like pressing, extrusion results in supports with lower porosity, better uniformity, smaller pore size, and higher mechanical strength, but it requires the mud material to have sufficient plasticity, flow characteristics, and uniformity to avoid deformation and cracking during the extrusion process [241].

5.1.3 Pressing method

The pressing method is a commonly used technique, and as shown in Fig. 18, it involves pressing a dry powder mixture, consisting of raw materials and pore-forming agents [235]. Once the powder is evenly blended (employing ratios of raw material to pore-forming agent), the resultant mixture is uniaxially compressed under stress via a punch within a mold featuring stationary walls. This process yields the intended shape of the membrane support [244]. With this technique, ceramic membranes with constant physical qualities and uniform porosity can be produced at high rates [245]. Examples include the manufacturing of tubular porous and supported ceramic membranes for microfiltration and ultrafiltration applications, as well as the preparation of low-cost ceramic membrane supports utilizing natural zeolite powder [246]. Two common approaches for dry powder compaction (containing < 2 wt% water) and semi-dry powder (holding ~ 5–20 wt% water) are uniaxial die pressing and isostatic pressing [143]. In the uniaxial die compaction, the powder material experiences simultaneous compaction and shaping within a rigid die [247]. This process can be further classified into two methods: hot and cold compaction. For cold pressing, a die is filled with a powder mixture, and then, uniaxial pressure is applied to form a green body (compacted powder). The hot compaction process is similar, but the green body is subjected to heating under a vacuum or inert gas atmosphere using induction [248].

5.1.4 Phase inversion method

Porous ceramic membranes, especially those with hollow fiber structures, can be produced using the phase inversion method [249, 250]. It is a de-mixing procedure that carefully transforms a homogeneous polymer casting liquid solution into a solid film [251]. This technique has previously been used to create porous silicon nitride and alumina hollow fiber membranes with success [249, 252]. In this study, the authors created tubular porous alumina ceramic support membranes using a self-designed phase-inversion casting technique, resulting in high-porosity tubular alumina membranes with a moderate flexural strength [253]. Alumina particles were combined with a polymer solution made of polysulfone (PSf) dissolved in N-methylpyrrolidone (NMP) [253]. As illustrated in Fig. 19, a homogeneous mixture was created by ball-milling the resultant suspension in order to create the tubular membranes [254]. This method involves pouring a degassed suspension into a casting device that is submerged in water, where it goes through a phase-inversion process and partially solidifies [253–255]. The green bodies are cut into circular pieces, heated to remove solvents and organic polymers, and then sintered at high temperatures to promote the formation of densely packed ceramic particles [254]. To create the final ceramic membrane, the green tubular membrane is then further solidified, dried, and fired in a furnace [253, 254]. Green tubular membranes' heating and sintering capabilities were characterized, and the relationship between porosity, pore size distribution, gas permeability, and mechanical strength during sintering was studied [253]. The findings demonstrated that phase-inversion casting generated membranes with better porosity, larger average pore size, and adequate mechanical strength when compared to membranes manufactured by cold pressing, demonstrating the viability of this manufacturing technique [253].

5.1.5 Sol–gel method

The sol–gel process is a flexible method for producing materials, notably ceramic compounds, by changing a solution (sol) into a solid (gel), and then, through carefully regulated drying and heating, into the appropriate end material [256]. The sol–gel technique is a commonly used method for creating ceramic membranes with specific pore sizes in the top layer [257]. There are two main approaches: first is the colloidal approach, in which a metal salt is combined with water to create a sol that, when coated on a membrane support, transforms into a colloidal gel. The second is the polymer approach, in which metal–organic precursors are combined with an organic solvent to create a sol that, when coated on a membrane support, transforms into a polymer gel [258]. The benefit of the sol–gel process is that, by varying the particle size in the sol, it is possible to manage the required pore diameters, especially for small pores [256]. It can be used to create coatings that are applied to non-bioactive materials in order to alter their characteristics and improve their biocompatibility, biocorrosion protection, or antibacterial capabilities [161, 259, 260]. In the sol–gel synthesis procedure, illustrated in Fig. 20, when hydrolysis is triggered,

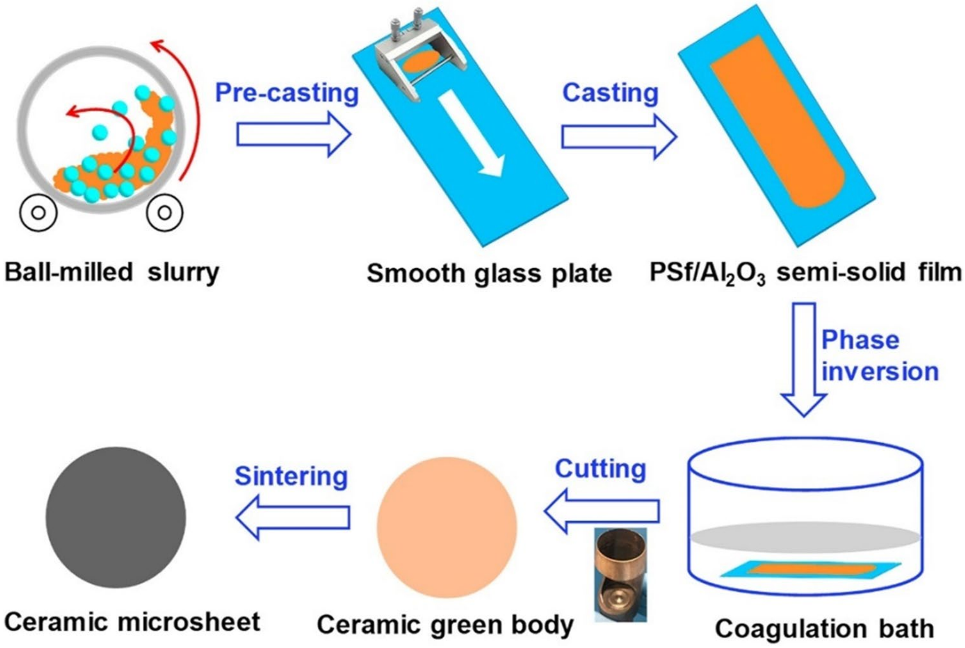


Fig. 19 Ceramic microsheet production via phase inversion [254]

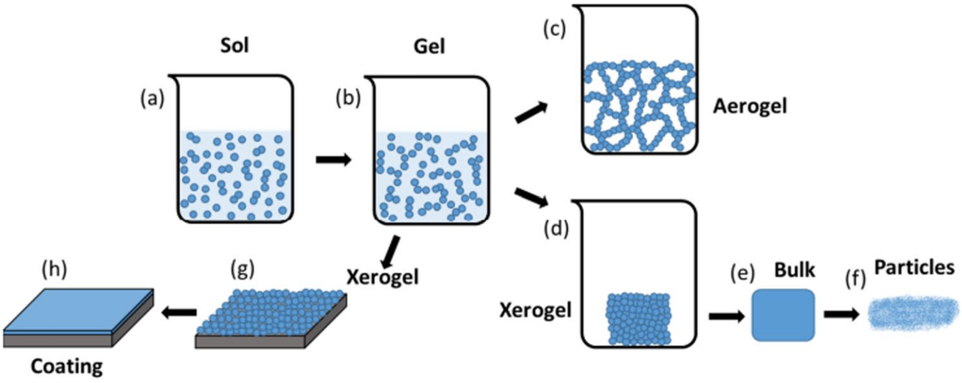


Fig. 20 Sol–gel procedure [260]

partially hydrolyzed molecules engage in a condensation response. This leads to the creation of more extensive molecules through the process of polymerization [260]. The second stage of the sol–gel procedure is initiated when these bigger molecules begin to randomly interact with one another and create a three-dimensional structure [260]. This stage involves the formation of a gel, which is a stable porous solid submerged in a liquid medium that fills the gaps in the three-dimensional structure [260]. The transition from sol to gel, known as gelation, causes a rapid increase in the viscosity of the solution [260]. After the gel forms in the sol–gel synthesis, removing the liquid phases from the gel is necessary to get a solid material. This is done through drying, which leads to two possible outcomes. When the liquid phase is eliminated using supercritical drying, it yields an aerogel [261]—a material that is largely air but contains about 1% solid [260]. Conversely, if the liquid is allowed to slowly evaporate under regular conditions, it results in a delicate solid known as a xerogel [262]. To achieve a dense, uniform material without pores, the xerogel undergoes sintering. For creating a coated surface, an extra step involves applying the sol–gel substance onto the substrate, followed by drying to acquire a xerogel coating [260, 262].

5.2 Preparation of Al_2O_3 porous ceramic membrane tube (PCMT)

The proposed method for preparing the single-channel Al_2O_3-based PCMT involved a combination of extrusion molding and solid-phase sintering techniques [263]. As illustrated in Fig. 21, the process begins with mixing α-Al_2O_3 powders of various grain sizes, carbon powders, SiO_2-Yb_2O_3, and kaolin in a V-type mixer for 5 h [263]. To aid in mixing, dibutyl phthalate (DBP) was used as a dispersant, while carboxymethyl cellulose (CMC) was added to bind all the components together [264]. Oleic acid served as a lubricating agent, and deionized water acted as both a solvent for mixing and to provide moisture. The ceramic paste obtained was further refined under vacuum conditions and then aged in a sealed container at 30 °C and 45% humidity for 3 days. Subsequently, a ceramic vacuum extrusion molding machine was used to

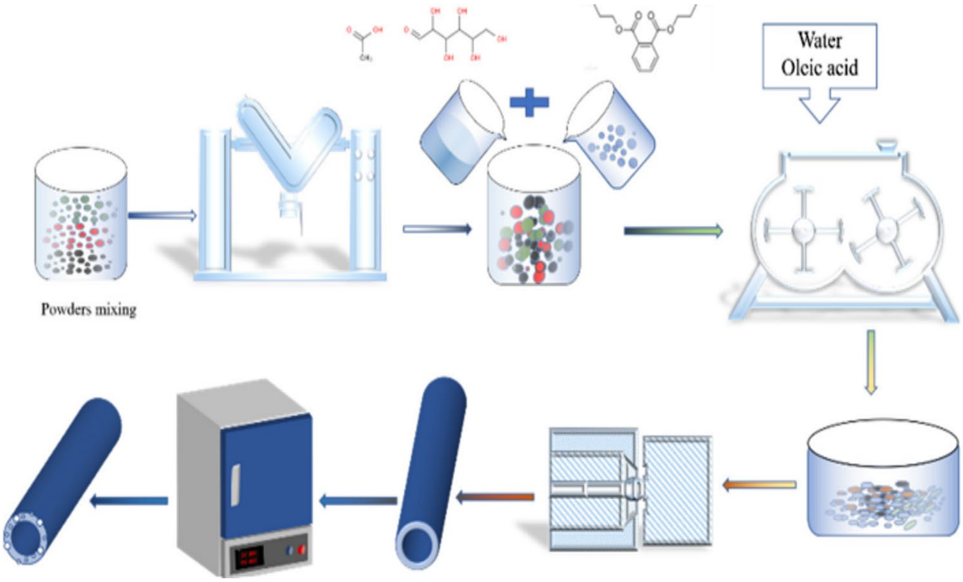


Fig. 21 Illustration of the preparation process of single-channel Al_2O_3-based PCMT [263]

form the single-channel ceramic tube embryo at a constant pressing speed [265]. After drying for 24 h at room temperature, the dried samples were sealed in an alumina crucible for protection in a lead atmosphere. The sintering process was then carried out at different temperatures, ranging from 1100 to 1200 °C, for 3 h [263].

6 Application of ceramic membranes in wastewater treatment

6.1 Ceramic membrane technology for the treatment of textile wastewater

The textile industry is notorious for generating large quantities of wastewater containing diverse pollutants, such as dyes, pigments, suspended solids, and organic compounds [266, 267]. Ceramic membrane separation has garnered significant attention as a reliable method for treating textile effluents [267–271]. As shown in Table 1, researchers have explored the use of Al_2O_3/TiO_2/ZrO_2 ceramic membranes with different molecular weight cut-offs (MWCOs) ranging from 1 to 500 kDa, resulting in substantial reductions in BOD, COD, TDS, turbidity, SS, and effective removal of dyes during textile wastewater treatment [132]. The study revealed that operating pressure, rejection rate, and permeate flux can be adjusted by selecting appropriate cross flow velocity (CFV), MWCO, and operational conditions [132]. Several cleaning methods were employed in the experiment, such as washing with tap water, deionized water, permeate, alkaline, and acid solutions, leading to approximately 90% recovery of membrane flux [271]. For instance, in a previous study, the effectiveness of ZrO_2-TiO_2 ceramic UF membranes in removing dye from a synthetic-colored feed solution was investigated, achieving a significant dye rejection of about 95% under optimal operating conditions [271]. Treating textile effluents is challenging due to the presence of persistent organic pollutants (POPs) and the varying composition of wastewater [272]. Advanced techniques, like using ceramic microfiltration (MF) and ultrafiltration (UF) as pretreatment before nanofiltration (NF) and reverse osmosis (RO), are recommended for textile wastewaters with high concentrations of COD/BOD and TDS [269, 273]. Ceramic membranes are preferred for their excellent chemical stability and resistance to harsh cleaning agents. However, their high initial cost hinders widespread application in large-scale textile plants [274].

6.2 Ceramic membranes for the treatment of petrochemical wastewater

Chemicals produced from gas and petroleum processes are referred to as petrochemicals. The petrochemical industry generates a considerable volume of wastewater containing diverse organic and inorganic substances, including oil compounds, dissolved minerals, and chemical compounds [283, 284]. Various research investigations have explored the utilization of ceramic membranes to treat petrochemical wastewaters. For instance, γ-Al_2O_3 ceramic membranes with a pore size of 0.2 µm were utilized to treat effluent contaminated with coke, achieving complete removal of coke and approximately 72% reduction in COD concentration [285]. Another study assessed the economic viability of employing γ-Al_2O_3 ceramic membranes for pretreating coke-contaminated wastewaters, showcasing their high efficacy in coke removal and potential as a cost-efficient approach for treating petrochemical wastewaters [285, 286]. Membrane technology offers advantages over conventional treatment methods in the petrochemical industry. However, there are challenges associated with membrane filtration, such as the accumulation of oil droplets on the membrane surface, leading to reduced permeation flux and membrane fouling due to complex fouling characteristics of petrochemical effluents [287]. In a previous study [288], ceramic α-Al2O3 membranes were tested for the removal of total organic carbon (TOC) from synthetic oil-in-water emulsion. The addition of powdered activated carbon (PAC) did not affect TOC removal, but it improved permeation flux and reduced fouling by providing a mechanical scouring effect [288]. Another experiment [289] involved the use of a kaolin/MnO_2 bi-layer composite on ceramic Al2O3 membranes, which showed excellent oil separation performance under various operational conditions, achieving a high permeate flux and oil retention ratio of 99% as shown in Fig. 22, but only in neutral or alkaline conditions due to the vulnerability of MnO_2 particles in acidic conditions [289].

6.3 Ceramic membrane for pharmaceutical wastewater treatment

The role of water is of utmost importance in pharmaceutical manufacturing. However, the wastewater produced during this process contains a diverse array of organic and inorganic compounds, including pharmaceutically active compounds (PhACs) and endocrine disrupting compounds (EDCs) [132]. Therefore, proper treatment of pharmaceutical effluents is critical to avoid the release of these substances into the environment and their potential adverse effects on the human health. In the pharmaceutical industry, ceramic membranes are gaining popularity due to their exceptional ability to endure repeated steam sterilization and harsh chemical cleaning, surpassing the capabilities of polymeric membranes [290]. Their successful application includes antibiotic recovery, filtration of fermentation broth, and “water for injection” treatment [291]. Utilizing ceramic membranes offers several benefits, such as longer lifespan, energy efficiency, and easier cleaning procedures [177]. These ceramic

Table 1 An outline of certain investigations evaluating the application of ceramic membranes to treat effluents from textile industry [132]

Operational parameters	Feed source and parameters	Membrane characteristics	MWCO/pore size	Flux	Rejection efficiency	Cost	Ref
TMP: 4 bar Temp: 25 °C CFV: 2.53 m/s	Synthetic colored solution with 50 mg/L dye concentration Conductivity (µS/cm): 44.35	Multichannel tubular ZrO_2–TiO_2 ceramic UF	MWCO of 150 kDa	255.86 L/m^2 h	Significant dye rejection around 95%	-	[275]
TMP: 3–13 bar	Biologically treated textile effluent from an activated sludge plant Conductivity (µS/cm): 8620 COD (mg/L): 329.4 TDS (mg/L): 4240	Tubular ZrO_2 ceramic UF followed by flat sheet polyamide NF	UF pore size: 50 nm NF pore size: 2 nm	At 11 bar TMP and VRF between 1 and 2.77: 40–45 L/m^2 h	Adding ceramic UF pretreatment before polymeric NF process guaranteed steady-state operation with longer constant and stable flux compared to direct NF	-	[276]
TMP: 1–3 bar Temp: 25 °C CFV: 3 m/s	Synthetic negative-charged dye solution with both inorganic salts NaCl/Na_2SO_4	Multichannel tubular tight UF ceramic membrane with TiO_2/ZrO_2 skin layer and porous Al_2O_3 support	MWCO: 8800 Da Pore size: 1.16 nm	15–70 L/m^2 h For TMP between 1 and 3 bar	Rejection of dye molecules: greater than 98% Rejection of NaCl < 10% Rejection of Na_2SO_4 < 30% Efficient to desalinate high salinity dyeing effluent and recover salts and dyes	-	[277]
TMP: 2–20 bar, Temp: 30 °C CFV: 3, 4, 5 m/s	Actual samples from a textile factory Conductivity (µS/cm): 2450–7780 COD (mg/L): 960–2525 Turbidity (NTU): 35.84–83.34	Multichannel tubular TiO_2–ZrO_2 UF ceramic membrane	MWCO: 30, 50, 150 KDa	90–160 L/m^2 h depending on CFV and MWCOs	Rejection efficiency (%) COD: 62–79 Color: 62–79 Turbidity greater than 99 For all MWCOs with the lowest CFV, higher removal of conductivity and COD achieved	-	[278]
Temp: 20 ± 1 °C and 50 ± 1 °C CFV: 1, 2, 3 m/s	Raw mercerization wastewater Conductivity (µS/cm): 75.100 TOC (mg/L): 499.20 Turbidity (NTU): 14.60 TDS (mg/L): 20957 TSS (mg/L): 100	Tubular multichannel ceramic UF 500 kDa: with Al_2O_3, TiO_2, ZrO_2 active layer 2 kDa: ZrO_2 active layer, Al_2O_3 support layer 1 kDa: ZrO_2 active layer	MWCO: 500, 2, and 1 kDa	Raw effluent flux with 1 kDa membrane: 29.01 L/m^2 h at the beginning 28.67 L/m^2 h at the end	Best rejection efficiency achieved by 1 kDa MWCO at CFV: 3 m/s ant temp: 20 °C SS: 92% Turbidity: 98% Color: 98% TOC: 53%	-	[279]
Temp: 25 ± 1 °C CFV: 3 m/s TMP: 1, 2, 3 bar	Simulated textile wastewater sample with various CMC concentrations	Tubular multichannel TiO_2–ZrO_2 ceramic UF	MWCO: 150 and 50 kDa	88.57–289.96 L/m^2 h depends on MWCOs and CMC concentrations	Removal efficiency regardless of operational conditions: Organic matter: 98.5% Dye: 93%	-	[280]
Pressure: 3 bar	Simulated textile wastewater sample prepared by deionized water and 0.25 g/L indigo powder Turbidity ≥ 1000	Ceramic membranes	Avg. pore size diameter of 0.14 µm and 0.60 µm		Permeate Indigo concentration: 0 Turbidity: 2–4	-	[280]

Table 1 (continued)

Operational parameters	Feed source and parameters	Membrane characteristics	MWCO/pore size	Flux	Rejection efficiency	Cost	Ref
Pressure: 1 bar	Textile dyeing effluent Conductivity (µS/cm): 6.16 Turbidity (NTU): 45.5 COD (mg/L): 3440	Ceramic MF membrane made of mineral coal fly ash	Avg. pore size diameter of 4.5 µm	100 L/m^2 h	Permeate quality: Conductivity (µS/cm): 5.38 Turbidity (NTU): 0.58 COD (mg/L): 880	-	[281]
TMP:0.4–1.2 kg/cm^2	Untreated sulfur black wastewater Conductivity (µS/cm): 36.9 Turbidity (NTU): 5912 COD (mg/L): 3910 TSS (mg/L): 5550 TDS (mg/L): 20.200 Dye concentration (mg/L): 890	Tubular multichannel α-alumina and clay ceramic MF	Apparent porosity 36%		Dye removal: 99%, COD reduction: 80%	-	[282]

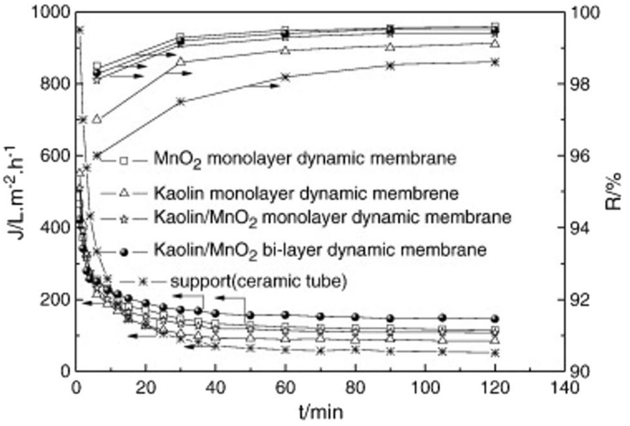


Fig. 22 Changes in permeate fluxes and retention ratios over time [289]

membranes not only provide superior filtration performance but also inhibit the growth of microorganisms, guaranteeing the production of high-quality pharmaceutical products [235]. Utilizing ceramic membranes in the pharmaceutical sector presents several advantages, including inherent biocompatibility, resistance to bacterial growth, and the capacity to endure repeated chemical and steam sterilization at elevated temperatures, a characteristic that poses challenges for polymer membranes [132]. The incorporation of ceramic ultrafiltration (UF) within a hybrid system for the production of ultrapure "water for injection" in medical applications serves as an effective measure to mitigate microbial proliferation and contamination in the piping system, particularly in scenarios where polymeric membranes lack resilience to periodic steam sterilization [132].

6.4 Ceramic membranes in pulp and paper industry

Ceramic membranes are being considered for treating wastewater in the pulp and paper industry due to their exceptional stability in harsh conditions [292, 293]. Unlike polymeric membranes, ceramic membranes can be effectively cleaned with harsh agents to prevent fouling or scaling, and they offer reliable performance over extended periods of operation [292, 294–296]. Various studies have evaluated the use of α-Al_2O_3 ceramic membranes with selective separation layers of TiO_2 or ZrO_2, which are readily available in the market with different pore sizes and MWCOs, for treating effluents from pulp and paper mills [297]. Ceramic membrane processes have been utilized to extract valuable materials, such as lignin, from pulp and paper wastewaters. Lignin, separated through ceramic membrane filtration, can be used for various purposes including biofuel, dispersant, blinder, emulsifier, and precursor for carbon fibers [298]. By adjusting the molecular weight cut-off (MWCO) of ceramic membranes, the fractionation of lignin can be controlled,

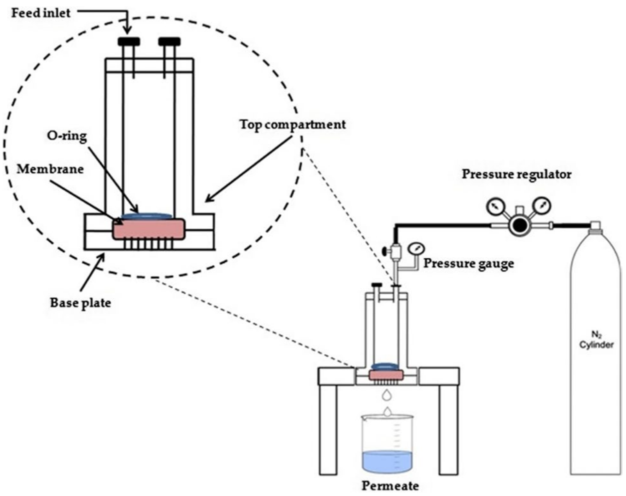


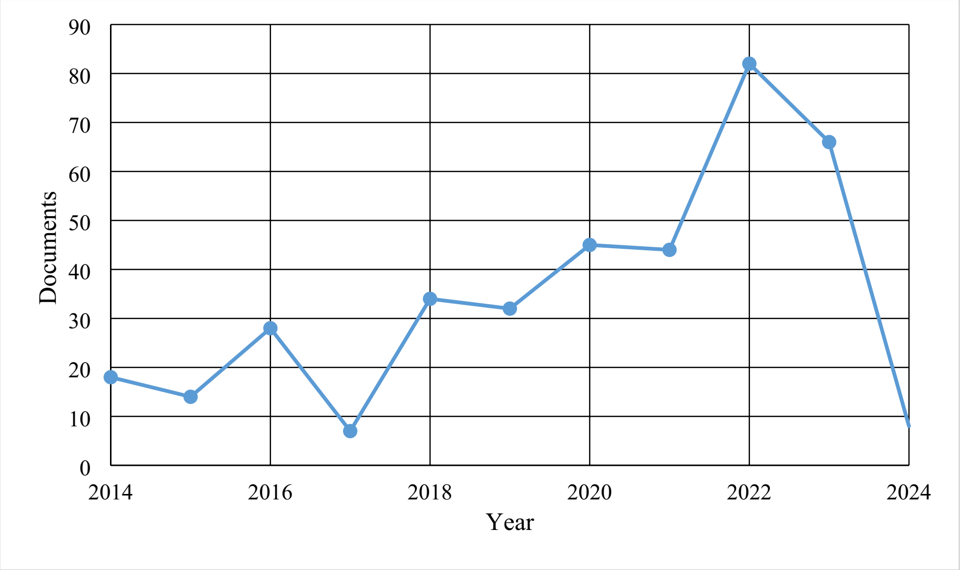
Fig. 23 Integrated biodegradation microfiltration experimental setup [302]

and applying ceramic ultrafiltration (UF) as a pretreatment step before polymeric nanofiltration (NF) can enhance the purity of the extracted lignin [299]. Comparative studies have shown that applying ceramic UF as a pretreatment before polymeric NF stages results in higher purity of lignin [300]. The paper and pulp industries generate substantial wastewater throughout various processing stages, including pulp production, bleaching, and deinking recycled paper. This wastewater is characterized by elevated levels of biological oxygen demand (BOD), chemical oxygen demand (COD), chlorinated compounds, absorbable organic halides, and total suspended solids [301]. Consequently, it is imperative to minimize these contaminants to meet environmentally acceptable limits before disposal, necessitating suitable treatment methods [301]. In a recent study [302], an integrated approach involving biodegradation followed by microfiltration for the treatment of wastewater from the paper and pulp industry was proposed. The microfiltration process with an experimental setup, as illustrated in Fig. 23, utilized a cost-effective ceramic membrane with a pore size of 1.01 µm and a porosity of 44%. The integrated approach demonstrated notable effectiveness, achieving an 87.6% reduction in COD and a 94.5% decrease in toxicity [302].

6.5 Full-scale application of ceramic membranes

Membrane biological reactors (MBRs) offer an alternative approach to traditional wastewater treatment methods, providing improved water recovery, reuse, and recycling [303]. One advantage of using MBRs in wastewater treatment, especially in rural areas, is their ability to effectively remove microbial pollutants like *Giardia* cysts and *Cryptosporidium* oocysts, which are considered reference pathogens for drinking water [303, 304]. However, MBR technology faces challenges such as membrane fouling, where the membrane surface and pores get clogged by microbial substances [305]. This study explores the use of low-cost ceramic membranes made from clay, calcium carbonate, potato starch, almond shell, and chamotte as a more affordable option compared to commercial ceramic membranes [303]. The researchers characterized the membranes, evaluated their performance in a laboratory-scale MBR [303, 306], and found that a membrane with a thin layer of TiO_2 demonstrated the best resistance to fouling and effective retention of contaminants such as *Escherichia coli*, *Cryptosporidium* oocysts, and *Giardia* cysts characterization of low-cost ceramic membranes for MBRs [306]. Membranes with a selective layer showed lower permeance and pore size, with the use of potato starch resulting in a sharper decrease in permeance

Fig. 24 Number of publications in ten years on the application of ceramic membrane in wastewater treatment



[303]. Membranes with a selective TiO_2 layer exhibited the smallest pore sizes and achieved high removal efficiency for *Giardia* cysts and *Cryptosporidium* oocysts, making them a competitive alternative for wastewater treatment [303]. The application of ceramic membranes in wastewater treatment has witnessed a surge in research interest, as evidenced in Fig. 24.

7 Future perspectives and concluding remarks

Ceramic membranes show immense promise in transforming wastewater treatment and environmental remediation. As the field advances, there are crucial future prospects that researchers and industries should explore to maximize the effectiveness and versatility of ceramic membrane technology. The future of this technology hinges on ongoing advancements and innovations. While commercially available ceramic MF and UF membranes have found widespread use in industrial settings, there is a need for further research to enhance the ease of fabrication, increase packing density, and reduce costs while consistently maintaining the quality of membranes. Moreover, research studies have revealed that the combination of oxidation processes and ceramic membranes holds great promise as an alternative to conventional water treatment methods, especially for the production of drinking water [227]. By integrating nanocomposites into ceramic membranes, these cohesive systems demonstrate enhanced performance in counteracting membrane fouling, streamlining system design, and supporting catalysis recovery [122]. Additionally, ceramic membranes exhibit lower fouling susceptibility and irreversible fouling compared to polymeric membranes due to their more hydrophilic surfaces [180]. To ensure dependable and long-term operation, further investigations are necessary to understand the influence of surface properties on membrane fouling and to analyze fouling agents. Furthermore, effective approaches for tackling biofouling challenges in ceramic membrane filtration should be explored. The challenges facing the advancement of ceramic membrane technology are comprehensive. Obstacles like the optimization of fabrication processes to simultaneously enhance simplicity, increase packing density, and reduce costs without compromising membrane quality are what cause the challenges with the use of ceramic membranes. Membrane fouling is another challenge that results in operational challenges, including lower membrane permeability that limits the overall plant capacity. Ceramic membranes also face challenges regarding membrane materials for certain applications where the use of polymeric membranes is not a viable option due to material limitations.

Ceramic membranes present a promising and versatile technology that holds great potential for wastewater treatment and environmental remediation. This comprehensive review has covered various aspects of ceramic membranes, encompassing their composition, fabrication process, filtration principles, and diverse range of applications. With the world facing escalating challenges concerning water scarcity and pollution, ceramic membranes offer a sustainable and efficient solution for wastewater treatment, safeguarding essential water resources. Moreover, the continual expansion of their applications, such as in removing emerging contaminants and recovering valuable resources, highlights the adaptability and relevance of ceramic membranes in addressing evolving environmental issues. As ongoing research progresses, ceramic membrane technology is poised to play a pivotal role in shaping the future of wastewater treatment and environmental remediation, leading us towards a cleaner and more sustainable world.

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Data availability All the data are available in the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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