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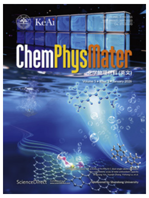

Review Article

Low-cost ceramic membranes: Manufacturing methods, cost analysis and application in water and wastewater treatment: A review

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ABSTRACT

Membrane technology is characterized by its low environmental impact, low energy consumption, and outstanding separation efficiency, making it a very promising alternative to other wastewater treatment processes. Ceramic membranes offer numerous advantages, including high thermal and chemical stability, high mechanical strength, outstanding durability, and excellent resistance to fouling. Recently, a great deal of research has gone into the manufacture of ceramic membranes with modified properties by varying the raw materials used. Choosing the right raw materials plays an essential role not only in optimizing membrane performance but also in reducing costs. This paper briefly describes raw material sources, characterization techniques, the different preparation methods used to manufacture ceramic membranes, and drying and sintering temperature. The paper also examines in detail the role of ceramic membranes in microfiltration and ultrafiltration processes for the treatment of water and wastewater with high concentrations of oils, chemical oxygen demand, turbidity, total suspended solids, and heavy metals. This mainly includes treatment of oily wastewater, textile effluent, tannery and dairy wastewater, paper industry wastewater, metal ion removal, bacteria and virus separation, and seawater treatment.

1. Introduction

Water is one of the most important natural resources for the continuation of life on Earth. It plays a central role in a wide range of human activities, from drinking and irrigation to industry, energy, and transport [1]. However, water resources are increasingly threatened by the acceleration of human activity, which is leading to unprecedented levels of pollution. This environmental degradation is due to some factors, including rapid population growth, uncontrolled urbanization, and the intensification of industrial and agricultural activities, which produce huge quantities of chemical and biological pollutants [2]. Factory wastes, such as heavy metals and toxic organic compounds, seep into rivers and lakes, while the excessive use of agricultural fertilizers and pesticides leads to the contamination of groundwater and surface water with nitrogen and phosphorus compounds, contributing to the phenomenon of eutrophication, which results in low oxygen levels in water bodies, affecting aquatic life [3]. In addition, untreated or partially treated wastewater carries pathogenic microorganisms, posing a direct threat to public health through the spread of waterborne diseases such as cholera and typhoid [4]. Dumping plastic waste and pharmaceutical pollutants into water sources exacerbates the problem, affecting the ecological balance of aquatic organisms and accumulating pollutants in the food chain [5]. Water pollution has become one of the most serious environmental challenges facing the world today, requiring integrated efforts that include implementing stringent wastewater treatment policies, promoting recycling techniques, and raising awareness of the importance of preserving water resources to ensure their sustainability for future generations. Water and wastewater treatment requires advanced, cost-effective, and efficient technologies to ensure clean, safe water for a variety of uses, whether for drinking, agriculture, or industry [6]. In the face of rising pollution rates and dwindling freshwater resources, there is an urgent need to find technologies capable of eliminating vari-

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ous contaminants, including suspended particles, heavy metals, organic pollutants, bacteria, and viruses, while ensuring environmental and economic viability [7]. Membrane technologies are one of the most popular solutions in water treatment due to their high efficiency in separating impurities and improving water quality [8]. They include microfiltration, ultrafiltration, reverse osmosis and nanofiltration [9]. These membranes effectively remove contaminants through fine physical barriers, making them an ideal choice for groundwater treatment, brine desalination and wastewater reuse [10].

However, traditional commercial membranes, whether made from polymers or advanced ceramics, face significant challenges that limit their large-scale deployment [11]. These include the high initial cost of purchasing and installing membranes, as well as high operating and maintenance costs, such as the periodic need for chemical cleaning and replacement of degraded membranes [12]. Some membranes also suffer from biofouling, i.e., organic and microbial contaminants accumulate on the membrane surface, resulting in reduced operating efficiency and increased energy consumption [13]. This economic and technical obstacle is more pronounced in developing countries and rural areas, where infrastructure lacks advanced treatment systems and many communities rely on unsafe water sources. Widespread use of membranes in water treatment requires the development of new high-performance, low-cost materials, such as hybrid membranes grafted with fouling-resistant nanoparticles, or the development of self-cleaning biofilms [14]. Investment in decentralized treatment technologies, such as low-pressure membrane systems and small, compact plants, can help improve access to clean, safe, and sustainable water [15]. Given the economic and environmental challenges facing water treatment, there is an urgent need to develop low-cost ceramic membranes based on locally available raw materials such as clay, kaolin, bauxite, rice husk ash, and recyclable materials [16]. These materials are abundant in many regions, making them an attractive option for minimizing manufacturing and supply costs [17]. In addition, the use of these local materials reduces dependence on imported materials, thus promoting economic sustainability and contributing to local development. Ceramic membranes are effective in water purification processes due to their high hardness and ability to withstand high temperatures [18]. Their porous properties enable them to separate various contaminants from water, such as suspended particles, heavy metals, and organic matter. Although traditional ceramic membranes are costly due to the materials used in their manufacture, the fact that they are based on local raw materials makes them competitive with more expensive commercial membranes [19]. To further reduce production costs, low-cost manufacturing techniques such as extrusion, where raw materials are pushed through a mold to form a homogeneous membrane, can be used to speed up the production process and reduce waste [20]. Slip casting can also be used, enabling ceramic membranes to be formed with high precision at low cost, thus improving membrane quality and reducing costs [21]. Immersion coating, which consists of coating a surface with a ceramic material by immersing it in an aqueous solution, is an effective and economical way of manufacturing membranes [22]. The adoption of these technologies will reduce operating costs and make the manufacture of ceramic membranes more competitive with traditional commercial solutions. In addition, these membranes can be a viable option for developing countries and rural areas that find it difficult to provide advanced water treatment solutions, making them a promising alternative that improves community access to clean, safe, and affordable water and contributes to long-term environmental and economic sustainability [23]. Demand for sustainable water treatment solutions is increasing dramatically worldwide, due to some interrelated factors. One of the most important is freshwater scarcity, a growing global challenge resulting from excessive water consumption, rapid population growth, and rampant urbanization. In addition, the effects of climate change are becoming more and more pronounced, significantly influencing available water resources. Rising temperatures are contributing to increased evaporation, while changes in precipitation patterns are leading to extreme fluctuations in water availability, creating new challenges in water resource management, particularly in areas dependent on seasonal rainfall or limited water sources [24]. In this context, it is essential to develop innovative, sustainable water treatment solutions that make efficient use of resources while minimizing environmental impact. Low-cost ceramic membrane technologies are one of the most suitable solutions, as they offer a combination of effective contaminant removal, the ability to treat low-quality water, and low costs compared with conventional solutions [25]. The importance of ceramic membranes lies in their ability to provide a cost-effective and sustainable method of treating water and wastewater [26]. They are capable of removing a variety of contaminants such as suspended particles, heavy metals, organic matter, and microorganisms, including bacteria and viruses, making them an ideal choice in many contexts, including remote areas or developing countries where advanced systems are unavailable or expensive [27]. Ceramic membranes also offer the advantage of energy savings, as many of them can be operated efficiently using low-pressure technologies, minimizing operating costs [28]. Thanks to innovative manufacturing techniques, such as the use of local raw materials and the development of low-cost production methods, these membranes can be produced at affordable prices, making them accessible to a greater number of communities, including in rural areas or countries lacking developed infrastructures. In addition to the economic benefits, ceramic membranes contribute to environmental sustainability. Their manufacturing process relies on recyclable materials such as clay, kaolin, and bauxite, minimizing the need for costly chemicals or synthetic materials that can be harmful to the environment. These membranes can be part of an integrated solution that enhances the sustainability of water sources by reusing treated wastewater or improving water quality in areas affected by pollution [29]. Providing efficient and sustainable water treatment solutions is essential to meet the growing challenges of climate change and water scarcity. Consequently, the use of low-cost ceramic membranes can be an important step towards sustainable management of water resources and improved access to drinking water worldwide, particularly in places where infrastructure is lacking. Ceramic membranes are an excellent choice for water treatment, as they feature several unique characteristics that make them superior to other membranes, such as polymeric membranes [30]. Firstly, ceramic membranes are highly thermally and chemically stable, which means they can withstand high temperatures and chemical pressures without degrading [31]. This feature makes them ideal for use in environments requiring high-temperature water treatment or exposure to aggressive chemicals, such as industrial water or wastewater treatment. These membranes are also highly resistant to biofouling, as they do not accumulate organic contaminants or microorganisms to the same extent as polymeric membranes, reducing the need for frequent cleaning and extending membrane life [32]. On the other hand, ceramic membranes last longer than polymer membranes, which can deteriorate more quickly due to UV exposure or chemical reactions with contaminants [33]. These advantages make ceramic membranes an attractive option in terms of performance efficiency and longevity, minimizing maintenance and replacement costs. The development of low-cost ceramic membranes represents an important step towards environmental sustainability by integrating the concept of the circular economy into membrane manufacturing processes [34]. The circular economy is defined as an economic system that aims to minimize waste and maximize reuse and recycling [35]. In this context, the development of low-cost ceramic membranes converts industrial and agricultural waste into usable raw materials, reducing the need for new raw materials and minimizing the environmental impact associated with the extraction of these materials [36]. Many industrial and agricultural wastes contain materials that can be of great value if properly reused. For example, certain types of waste such as rice husk ash, industrial clay and bauxite from mining operations can be transformed into essential raw materials for the manufacture of ceramic membranes [37]. These materials are collected from a variety of sources, including factories, farms, and mines, then processed and reused in production instead of being discarded as waste.

When these wastes are used as raw materials, the pressure on natural resources that are normally extracted from nature is minimized, helping to preserve the environment. This approach also reduces the cost of raw materials and improves the feasibility of low-cost ceramic film manufacture. The incorporation of recycled materials in the manufacture of ceramic films is a concrete way of promoting the concept of the circular economy [38,39]. In this model, raw materials are not just an input into the production process but form part of a closed cycle in which they are reused ad infinitum, minimizing the need to extract new materials and reducing waste. Furthermore, the ceramic membranes themselves can be used sustainably, as they can be recycled at the end of their service life, promoting long-term sustainability [40]. The reuse of waste materials in the manufacture of ceramic membranes minimizes the need for complex, energy-intensive manufacturing processes [41]. For example, instead of extracting new raw materials, which often require a great deal of energy to transport and process, local recycled materials can be used, reducing energy costs and the associated carbon footprint. The manufacture of ceramic films from these materials can be carried out using less energy-intensive manufacturing techniques, such as extrusion or slip casting, which also help to reduce carbon emissions. In addition, the use of these recycled materials in different industries can improve the overall efficiency of industrial processes, reducing dependence on fossil fuels and minimizing the negative environmental impacts associated with the extraction and processing of raw materials. This helps to improve the sustainability of industrial processes in general, and reduce the environmental impacts resulting from greenhouse gas emissions that contribute to global warming. Consequently, the development of low-cost ceramic membranes using recycled materials represents an innovative and sustainable approach to water treatment. This approach not only improves the efficiency of the water treatment process but also significantly reduces the impact on the environment, both by minimizing the use of new raw materials and by reducing the carbon footprint associated with manufacturing. This evolution is part of a wider movement towards environmental and economic sustainability and promotes the application of the circular economy in a variety of industries, paving the way for the development of sustainable environmental solutions that improve quality of life and minimize the effects of climate change. Although there is a great deal of research into ceramic membranes, most of it focuses on optimizing performance without considering cost. This study aims to provide a comprehensive analysis of low-cost ceramic membranes by reviewing the latest research on their manufacturing techniques, raw materials used and cost analysis methods, focusing on different industrial applications for water and wastewater treatment. This study combines a scientific, technical, and economic analysis of ceramic membranes, reviewing the different manufacturing techniques, raw materials, and associated challenges, with an emphasis on the development of low-cost solutions. The study also includes a comparative analysis of production and utilization costs, enabling researchers and practitioners to make informed decisions on how best to apply this technology. To ensure that all aspects related to low-cost ceramic membranes are covered, the study will discuss the different categories of membranes used in water treatment, including organic and ceramic membranes and the differences between them. The differences include the raw materials used in the manufacture of low-cost ceramic membranes, the analytical methods used to study the composition of these materials, the different methods of film manufacture, focusing on low-cost processes such as extrusion, slip casting and pressing, the different sintering programs and their effects on the structure and properties of ceramic films. It will also include the methods used to analyze the properties of manufactured membranes, such as porosity, shrinkage, mechanical strength and filtration tests, the mechanisms of fouling and its impact on membrane performance, as well as methods to minimize it. Furthermore, the use of ceramic membranes in industrial wastewater treatment will be analyzed in detail, as will the costs associated with the manufacturing and operating of low-cost membranes for water treatment by membrane separation. This study aims to provide an overview of the potential for low-cost manufacturing of ceramic membranes, to analyze the factors affecting final cost, and to provide practical solutions to overcome the challenges associated with production and use. The impact of various factors such as raw material type, manufacturing techniques, and heat treatment schedules on membrane quality and production costs will also be assessed. This study will provide an integrated framework for understanding how ceramic membranes can be manufactured at low cost without compromising efficiency, paving the way for wider application in water and wastewater treatment.

2. Membranes classification

The scientific community has classified membranes according to various parameters: separation mechanism, fouling, service life, chemical, mechanical and thermal resistance, morphology, pore size and, finally, the raw materials used in membrane preparation [42–44]. These materials include inorganic materials such as clay, titanium, silica, alumina, zirconia and zeolites [45–48], polymers [49], hybrid materials by mixing organic and inorganic materials and biological materials [50,51]. The membrane market is highly diversified, with ceramic membranes accounting for around 26% [52]. Ceramic membranes are often the most suitable for industrial wastewater treatment because of their very high resistance to biodegradation, excellent chemical resistance, resistance to high pressures, long service life and easy regeneration [53]. To produce high-quality ceramic membranes, several essential criteria must be taken into account, such as heat treatment, deposit formation, porosity, high permeate flux, and chemical and mechanical resistance [54]. There are two methods for separating rejects through ceramic membranes: cross-flow tangential filtration and dead-end flow frontal filtration [55,56]. Fig. 1 shows the membrane classifications according to manufacturing material.

3. Raw materials composition

The ceramic membranes were manufactured using inorganic materials as raw materials. Several ceramic membranes were prepared from local mineral clays from various regions, such as Morocco, Tunisia, and Kashmir [57–59]. These clay materials include diatomite and natural zeolite [60], kaolin, zirconium oxide (ZrO_2), titanium dioxide (TiO_2), and fly ash [47], zirconia (ZrO_2), alumina (Al_2O_3), quartz, apatite, and various industrial wastes [61,62]. Clays have been particularly studied as the preferred raw material for these applications. The composition of the raw material as well as the particle size of the powder significantly influence porosity, mechanical strength, chemical resistance in acidic and basic media, and average pore size. Amine et al. [63] fabricated ceramic membranes from different CuZn compositions, ranging from 0 to 40% by weight, combined with 80% by weight clay, 5% by weight carbon, 10% by weight TiO_2 and 5% by weight PVA. It was also observed that membrane porosity increased from 44.58% to 66.67% when CuZn content increased from 0 to 10%, before decreasing to 55.13% with a CuZn content of 40%. Dhivya et al. [64] manufactured ceramic membranes (S1–S3) from ball clay, China clay, quartz, and calcium carbonate, varying the percentages of these components. Porosity was found to vary from 44% to 41%. The composition of the raw material has an effect on porosity.

4. Raw material characterization technique

4.1. X-ray fluorescence (XRF)

The chemical composition of the clay powder was detected using energy dispersive X-ray analysis. The XRF technique is based on the emission of fluorescent X-rays through elements excited by bombardment with very high-energy X-rays [65]. The oxides making up clay materials include silica (SiO_2), alumina (Al_2O_3), calcium oxide (CaO), sodium oxide (Na_2O), magnesium oxide (MgO), iron oxides (Fe_2O_3),

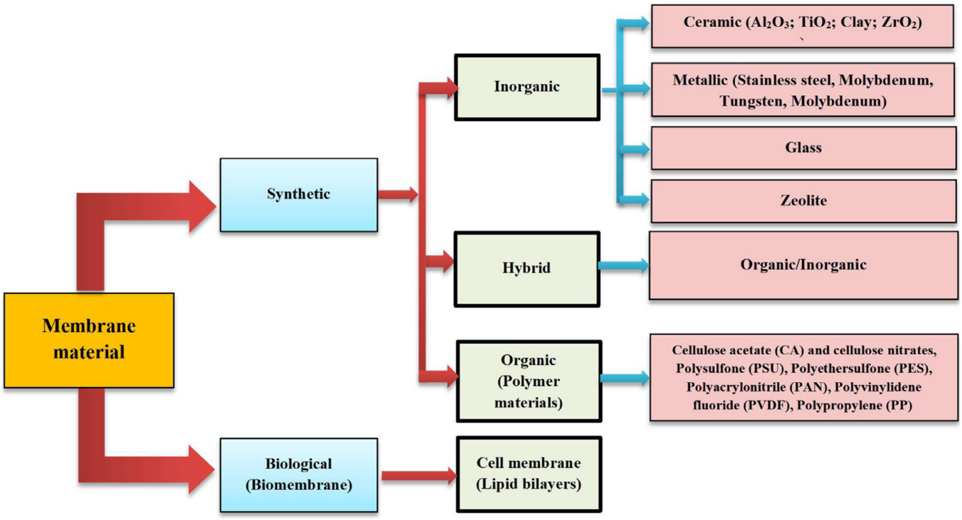

Fig. 1. Membrane classification according to raw materials used in production.

potassium oxide (K_2O), and titanium dioxide (TiO_2) [65–67]. The particularly high SiO_2/Al_2O_3 ratio indicates the presence of quartz and/or amorphous silica [68]. Rani and Kumar characterized Fuller's clay using the XRF technique. Its chemical composition includes SiO_2 (63.33%) and Al_2O_3 (19.17%), as well as Fe_2O_3 and traces of K_2O, TiO_2, CaO, and SO_3 [69]. Belgada et al. characterized the phosphate. The results show that phosphate is mainly composed of P_2O_5 (32.3%) and CaO (49.3%) oxides. In addition, it contains minor quantities of impurities, such as silica, alumina, magnesia, and iron oxide [43]. Elgamouz et al. carried out the chemical analysis of natural clay. The results show that the clay is mainly composed of silica, calcium oxide, and alumina, with a low presence of other oxides such as MgO and K_2O [70].

4.2. Fourier-transform infrared spectroscopy (FTIR)

The FTIR study aims to detect the different chemical functions existing in membranes. For example, for OH stretching, the extensible band is 3653, 3694, and 3620 cm^{-1}. The Si-O stretch is 469, 680, 1000, 1030, and 1150 cm^{-1}. This was 528, 789, 750, and 754 cm^{-1} when Si-O-Al was detected. The presence of this group has a significant impact on the adsorption process, increasing the zeolite content and, at the same time, increasing the metal ion cut-off [71,72]. Si-O-Si stretching was detected at 1110 cm^{-1}. The bands with intensities of 917 and 910 cm^{-1} correspond to the Al-OH bond [45,66,73]. Bands between 453.68, 557.43 and 673.53 cm^{-1} distinguish the presence of phosphate groups ($PO_4{}^{3-}$) [74]. The symmetrical stretching vibration of the carbonate group is detected at 1460 cm^{-1} [75]. The deformation vibration band of O-Si-O is 735.19 cm^{-1} [76]. The C–H stretching vibration and the C=O bonding vibration were detected at 2920 and 1731 cm^{-1} respectively. C=C stretching vibrations associated with bands 1613 and 1512 cm^{-1} and C–O stretching vibrations detected at 1316, 1233, and 1021 cm^{-1} [77]. The vibrational bands visible at 677 cm^{-1} are due to Fe-O and Ti-O bonds [78]. The vibrational stretch of Al-O is determined by a band at 689.30 cm^{-1} [79]. The Al-OH deformation vibration band is 918 cm^{-1}. The Mg-O-Si bending vibration is detected in the peak at 525 cm^{-1} [65]. The symmetrical vibrations of the $NO_3{}^-$ group are linked to a band at 1332.91 cm^{-1} [80]. Ti-O-Ti is visible in the bands at 1000 cm^{-1} [81]. The 3412 cm^{-1} band corresponds to the -OH stretching vibration located in the Al-OH-Al, Mg-OH-Al, and Fe-OH-Al groups [65].

4.3. X-ray diffraction (XRD)

Clays consist mainly of alumina, silica, and water, and also contain varying amounts of iron, alkali metals, and alkaline-earth metals [65]. XRD analysis identifies all the phases and mineralogy that make up the raw clay. These include gypsum (G), kaolinite $Al_2Si_2O_5(OH)_4$ (K), carbonate (C), illite (I), quartz SiO_2 (Q), mullite $2Al_2O_3SiO_2$ (Mu), pyrophyllite, anorthite $CaAl_2Si_2O_8$ (An), rutile (R), hematite (α-Fe_2O_3), calcite $CaCO_3$ (Cal), felspar (F), iron carbide, muscovite $KAl_2(Si_3Al)O_{10}(OH, F)_2$ (M), lepidocrocite (γ-FeO(OH)) (L), chlorite (C), dolomite (D), gehlenite $Ca_2Al[AlSiO_7]$ (G), and phengite (P) [66,78,82–84]. The phases were characterized by interreticular distances, Miller indices, and 2θ position. The peaks corresponding to 3.341 (113), 9.167 (002), 4.590 (004), 2.425 (117), 3.062 (006), and 1.368 (316) are single pyrophyllite peaks. The quartz phase is characterized by peaks at 3.35, (101), 26.7°; 4.27, (100), 20.9°; 2.45, (110), 36.5°; 2.12, (200), 42.5° and 1.81, (112), 50.1°; 3.343 (101) and 1.817 (112). The triclinic kaolinite phase was found at 7.17, (00l), 12.3°; 4.47, (020), 19.8°; 3.57, (002), 24.8° and 2.38, (003), 37.9°. The illite phase was observed at 10.0, (002), 3.34, (006), 26.6° and 8.7°; 5.02, (004), 17.6°. The carbonate phase was observed at 3.84, (012), 23.1°; 2.83, (113), 39.5°; 3.04, (104), 29.4° [85,86]. The peak at $2\theta = 12.55°$ can be associated with chlorite [68].

4.4. Thermogravimetric analysis (TGA) and differential thermal analysis (DTA)

A thermal study aims to determine the temperatures at which most of the weight loss occurs and therefore a real change takes place [87]. DTA analyses illustrate endothermic and exothermic peaks. An endothermic peak corresponds to the removal of wet and absorbed water from the sample at around 95 and 120 °C [45,65]. An endothermic peak occurs between 400 and 557 °C, due to the decomposition of kaolinite into metakaolinite, and the other peak occurs between 630 and 736 °C, due to the destruction of carbonates [88,89]. The gradation of pyrite and traces of pyrrhotite at 750 °C indicated by an exothermic peak [84]. An endothermic peak occurs at 561 °C, corresponding to the transformation of quartz [65]. TGA analysis indicates weight loss when a sample is heated. The main purpose of this thermal analysis is to determine the temperature regimes where the membrane exhibits greater weight loss and phase changes to determine the optimum sintering temperature [90]. Nandi et al. determined a weight loss of 10% corresponding to the production of CO_2 during the calcination of $CaCO_3$ [89].

4.5. Scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX)

The scanning electron microscope (SEM) is an essential tool for characterizing ceramic films. It provides high-resolution images of the material surface and facilitates the study of morphological structure and surface homogeneity. SEM relies on the use of a focused electron beam to scan the surface of a sample, generating secondary and reflected electrons that are used to create a detailed image of the surface. This technique enables surface characteristics such as porosity, pore size, cracking, and structural regularity to be analyzed, making it possible to assess membrane quality and identify defects that may affect its performance. In addition, scanning electron microscopy can be combined with elemental analysis techniques, such as energy dispersive X-ray analysis (EDX), to get more detailed structural information. Energy dispersive X-ray analysis (EDX) is an analytical technique used in conjunction with SEM to reveal the elemental composition of ceramic films. The technique is based on the detection of X-rays emitted by the sample as they interact with the electron beam of the microscope. This analysis enables precise identification of the chemical elements present in the membrane, making it possible to determine its purity, the presence of any impurities, and the distribution of elements on the sample surface. EDX is also used to identify compositional changes between different regions of the membrane, particularly when there is a variation in composition or the introduction of elements modified to improve the material's physical and chemical properties. This technique is essential in the study of multicomponent membranes, as it can reveal the homogeneity of elements in the sample and verify the success of chemical modification or modification processes.

4.6. *Particle size distribution (PSD)*

Analysis of particle size distribution is an important factor in the characterization of ceramic membranes, as it significantly affects physical properties such as porosity, permeability and mechanical stability. This analysis is carried out using various techniques such as dynamic light scattering (DLS), laser dispersion (LD) or scanning electron microscopy (SEM) combined with image analysis software. This analysis can be used to determine average particle size and dispersion, helping to optimize preparation methods and operational parameters. Large variations in particle size lead to undesirable effects such as agglomeration or irregular pore distribution, which can reduce membrane efficiency in industrial applications. It is therefore essential to control particle size distribution to guarantee homogeneous, optimized ceramic membrane performance.

5. Ceramic membrane manufacturing methods

Ceramic membranes are produced in various forms, such as tubular, flat, and hollow fiber. Once the raw material has been selected, it is ground using a ball mill. The powder obtained is then sieved using an electric sieve. The granulometry of the selected sieve is estimated in μm [91]. The technique used to shape ceramic membranes depends on the state of the paste (dry or wet) and the desired structure (flat or tubular). Several techniques are used for shaping membranes, such as extrusion [92], paste casting [93], slip casting [94], powder pressing [95], tape casting [19], freeze casting [96], and dip-coating [97]. The ceramic membranes formed were sintered in an electric muffle furnace at different temperatures according to a thermal program [46].

5.1. *Extrusion method*

Extrusion is a widely used technique for manufacturing ceramic tubes. The raw material is mixed with materials such as plasticizers and binding agents to form the paste [98]. The resulting paste is forced through a die into a tabletop extruder to form a tubular membrane using a relatively simple piston press [99]. A clear illustration of membrane manufacture is shown in Fig. 2(a). After two days' aging, the paste was extruded into tubular supports, dried at 40 °C for 24 h, and then sintered at sintering temperature [94]. Yang and Tsai developed tubular ceramic supports from a mixture of alumina, bentonite, starch, and deionized water. After an aging time of 48 h, the extruded paste was dried overnight at room temperature and then sintered at (800, 1000, and 1200 °C) [100]. Dahiya et al. have developed a tubular ceramic membrane using the extrusion technique with ball clay. The membrane was sintered at a sintering temperature of 1000 °C [101]. Oun et al. prepared it from a mixture of dry kaolinitic clay, alumina, and Methocel powder. Tubular ceramic supports were produced by extrusion, followed by drying at room temperature, then sintering at 1350 °C [102]. Satyannarayana et al. have developed a tubular ceramic membrane using bentonite clay, rice husk, ash and activated carbon. The paste was shaped by extrusion, then the resulting membrane was sintered at 900 °C [103]. Vinoth Kumar et al. developed a tubular ceramic membrane by mixing ball clay, kaolin, feldspar, quartz, pyrophyllite, and calcium carbonate. The resulting paste was extruded to shape the membranes, which were then sintered at 950 °C. These membranes have a mechanical strength of 12 MPa [99].

5.2. *Slip casting method*

Slip casting is a very interesting technique, as it is a water-based process that allows great flexibility in the composition of the slip and its combination with other processes [104]. In this technique, the suspension is carefully mixed and then poured into a porous mold. It then diffuses through the pores under the effect of a driving force, forming an extremely thin layer on the inner surface of the mold [105]. The time required to fill the suspension varies according to the desired thickness, followed by a drying phase and heat treatment [106,107]. Fig. 2(b) illustrates the slip casting process, from preparation of the suspension to formation of the filter layer on the membrane's inner surface. Slip casting is used to manufacture various types of ceramic membranes from different materials, such as membranes based on silty marl, microfiltration membranes based on leached phosphate, and those made from refined fly ash and alumina [108–111]. The ceramic membranes produced by this method are distinguished by their excellent permeability [112]. Iaich et al. developed a low-cost tubular ceramic membrane using Moroccan clay. The paste was extruded to form tubular supports, onto which a microfiltration layer was deposited by slip casting on the inner surface [113]. Jedidi et al. manufactured fly ash-based ceramic tubular supports using the extrusion method, intended for the treatment of textile dyeing effluents. The fly ash layer was deposited on the support using the slip casting process [114].

5.3. *Paste casting method*

Membranes are manufactured by hand, with or without the use of a machine, using a mold that may or may not be porous. Paste casting is the most conventional and simplest technique compared with other manufacturing processes. The pressure applied does not require a hydraulic press [115]. In this method, various raw materials are mixed under suitable conditions and then ground using a mill. Distilled water is then gradually added to form a homogeneous paste [116]. The paste is placed in circular molds to form disks. After 30-h of natural drying at room temperature, the disks are gently removed and dried at 100 °C for 12 h. The disks are then sintered in a programmable muffle furnace set to the desired sintering temperature. Finally, the furnace temperature is allowed to drop freely to room temperature [93]. Fig. 2(c) illustrates the various steps involved in forming the ceramic membrane. Lagdali et al. have produced a phengite clay-based ceramic membrane using the paste casting method, intended for wastewater microfiltration. The membrane, sintered at 1050 °C, has a porosity of 34.5% and a mechanical strength of 26.7 MPa [117]. Agarwalla and Mohanty produced a ceramic membrane based on natural kaolin clay, using the paste casting method, for the microfiltration of methylene blue dye. Sintered at 850 °C, the membrane showed a reduction in porosity, from 34.52% to 21.5%, as the percentage of binder increased from 8% to 20%. At the same time, flexural strength increased from 7.1 to 9.4 MPa [45].

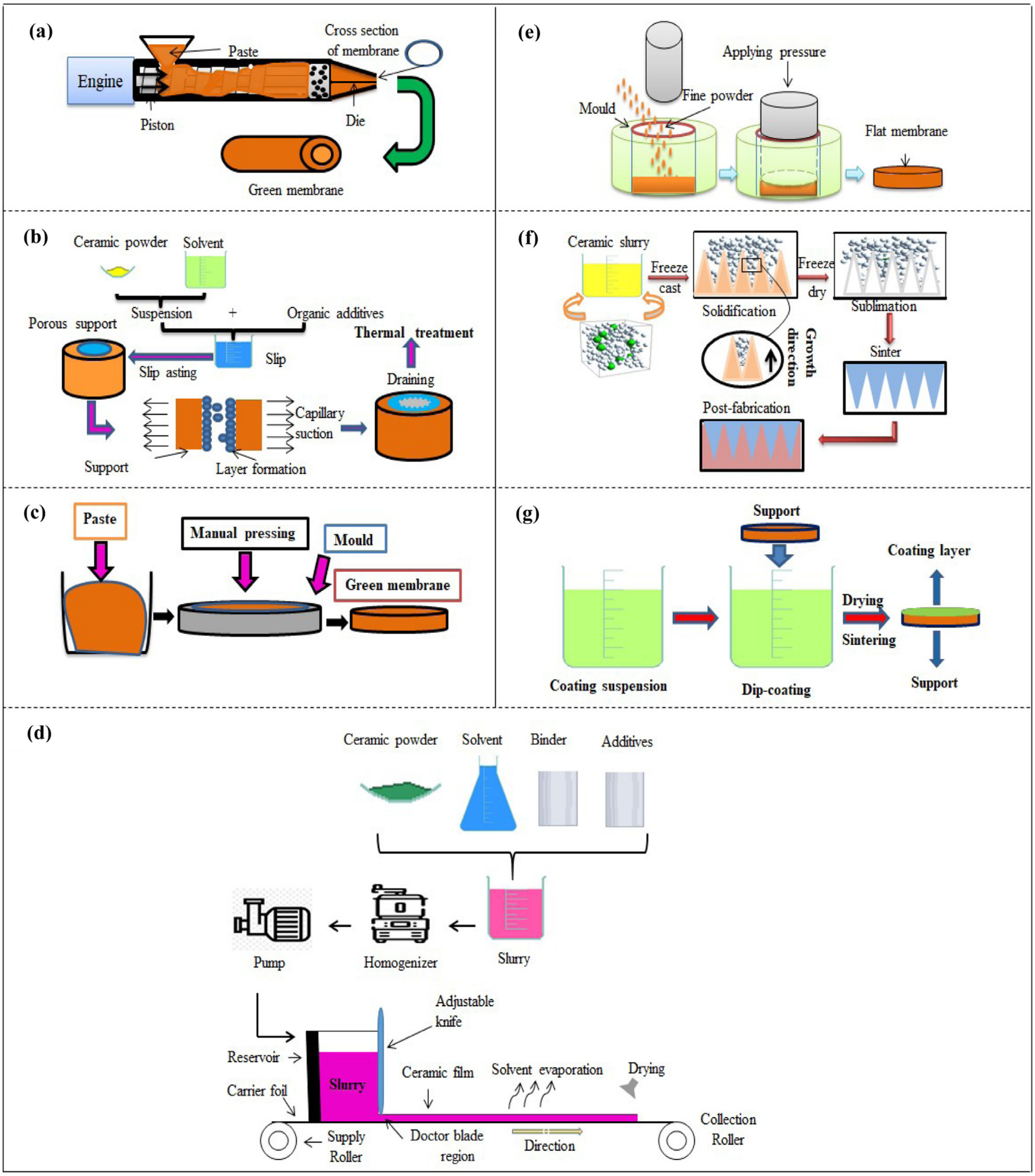

Fig.2. Different methods for preparing ceramic membranes (Extrusion method (a), Slip Casting method (b), Paste Casting method (c), Tape Casting method (d), Powder pressing method (e), Freeze Casting method (f) and Dip Coating method (g)).

5.4. Tape casting method

Tape casting is a manufacturing technique widely used to produce thin, smooth ceramic sheets. The technique was created by Glen N. Howatt in the mid-1940s [19]. Strip casting is mainly based on the preparation of a suspension in which ceramic powder is dispersed in a solvent with the addition of binders, dispersants, and plasticizers [118]. This technique is used to produce thin, flat ceramic sheets with a thickness range from 10 µm to 1 mm [119]. The suspension is spread on a flat surface by an adjustable knife called the doctor blade. In some cases, film lengths of up to hundreds of meters can be produced [120]. The general procedure for manufacturing ceramic foil is shown in Fig. 2(d). The suspension is poured into a tank and passed through an adjustable doctor blade, from which the thickness of the foil is set. The resulting film is then dried to evaporate the solvent, either by thermal conduction, hot air circulation, or infrared radiation, thus reducing its thickness [121]. Tape casting offers many advantages, making it a particularly promising manufacturing process. It enables a wide range of materials to be cast and powders of various chemical compositions to be combined within a single belt [120]. Wang et al. have succeeded in producing an $Al_2O_3/CaAl_{12}O_{19}$ ceramic membrane using a combination of emulsion, cement polymerization, and tape casting techniques [122]. Coelho et al. have designed an Al_2O_3 membrane using a combination of tape casting and phase inversion techniques for microfiltration applications. The total porosity of the membrane is high, ranging from 46% to 75%, while the mechanical strength varies between 27.60 and 41.11 MPa, depending on the alumina content of the sludge, which varies between 45% and 50% by weight [123].

5.5. *Powder pressing method*

The pressing technique is widely used by scientific researchers to manufacture circular or disc-shaped ceramic membranes, particularly in laboratory research [124]. Generally speaking, there are two pressing processes: axial pressing (uniaxial and biaxial) and isostatic pressing, which have been used to manufacture ceramic membranes [34]. In this technique, the raw material is dried to remove moisture, crushed, and then sieved according to the grain size chosen. In some cases, the powder is mixed with a few additives (pore-forming agents, plasticizers, binders, etc.). The homogeneous powder is introduced into a stainless steel mold. A hydraulic press is used to apply uniaxial pressure to obtain the desired flat shape. Finally, the membrane is sintered at the desired temperature according to a precise thermal program [44,46,125,126]. The isostatic pressing process is divided into cold isostatic pressing and hot isostatic pressing [115]. Fig. 2(e) shows the uniaxial pressing process. Arkame et al. developed flat ceramic membranes from Moroccan lizardite clay. The powder was subjected to a pressure of 10 tons for 15 min using a hydraulic uniaxial press. Sintering was carried out at a temperature of 1100 °C, and the mechanical strength obtained was 19.3 MPa [127]. Rahma et al. developed flat membranes from used bleaching earth (SBE). The sample was pressed at a pressure of 4 to 7 MPa in a flat disk mold, then sintered at 800 °C [128]. Xavier et al. have developed a membrane designed for seawater treatment. To achieve this, they mixed steel slag with distilled water to obtain a paste at a concentration of 10% m/v. This paste was then shaped into a flat disk using a uniaxial press applying a pressure of 25 MPa. The optimum membrane, consisting of 20% slag by weight, was sintered at a temperature of 1150 °C [48].

5.6. *Freeze casting method*

Freeze casting, also known as ice modeling, is a particularly interesting technique for the manufacture of carbon, metallic, polymeric, ceramic, composite, and bio-macromolecular materials with a porous structure and specific architecture [129–131]. The manufacturing method is illustrated schematically in Fig. 2(f). The suspension was prepared by mixing a ceramic powder, a solvent, an organic binder, and a dispersing agent. The suspension was poured into a mold, frozen on a cold surface, and then sublimated in a freeze-dryer under reduced pressure and temperature conditions. Finally, sintering was carried out in air at a constant heating rate. The formation of the porous structure is based primarily on the growth of solvent crystals, resulting in the rejection of ceramic particles [132]. The solvent is stimulated to grow vertically and form macropores aligned in the same direction. Pore formation is mainly linked to the separation of the two phases of solvent and ceramic particles [133]. Porous ceramics obtained by this process have the following characteristics: high porosity and an open porosity structure [134]. Hong et al. prepared a highly porous ceramic based on zirconia and camphene, with a solids content ranging from 10% to 20% by volume. After sintering at 1500 °C for 2 h, flexural strength varies from 41 to 63 MPa, while pore size in the microstructure ranges from 20 to 50 μm [96]. Hautcoeur et al. used the same method to produce an anisotropic porous ceramic based on alumina. Pore sizes ranged from 6 to 42 μm and from 13 to 300 μm, depending on powder content, binder content and freezing rate. Calculated values for elasticity and strength ranged from 0.2 to 14 GPa and from 6 to 111 MPa respectively. The proportion of pores ranged from 40% to 57% [135].

5.7. *Dip coating method*

Fig. 2(g) shows the immersion coating technique. The substrates are immersed in the solution, then left to air-dry for a set time. This process was repeated several times. Finally, the immersed substrates were calcined in an oven to form thin coatings. It is important to note that only one side of the support was immersed in the coating suspension, while the other side, held above the surface of the suspension, remained constantly parallel to it [97,112,136]. Bouazizi et al. developed a natural bentonite-based support using the pressing method. The ultrafiltration layer, made from nano-TiO_2, was applied by the dip-coating technique [137]. Marzouk et al. developed TiO_2/SiO_2 ceramic membranes by coating commercial TiO_2 ceramic membranes with silica nanoparticles (SiO_2). Among the membranes developed, the best performing, designated M2, was selected for its total organic carbon removal efficiency, reaching 91%, and its high flux of 3636 LMH [138]. Yang et al. developed ceramic nanofiber membranes based on attapulgite (APT). A flat-sheet α-alumina ceramic support was immersed in a coating suspension. After sintering at 600 °C, the resulting membrane exhibited high porosity and excellent permeability [97]. Zhu et al. developed ceramic membranes by adopting the immersion coating method. Porous tubular alumina supports were arranged vertically and filled with suspension. The disc-shaped support was deposited on the surface of the suspension, keeping its flat face parallel to that of the suspension [139].

5.8. *Spin coating method*

Spin coating is a very promising method for preparing flat composite membranes in the laboratory [140]. In this process, a flat support rotates around a vertical axis, and the film-forming solution is deposited on the support perpendicular to its surface during rotation. To control the thickness of the membrane layer, by modifying these parameters: rotation time and speed, solution concentration, and quantity deposited [141]. In comparison with several techniques such as electrochemistry, physical/chemical vapor phase, and other preparation methods. Spin coating is a gentle, easy-to-control membrane manufacturing process [142]. Xie et al. have developed high-performance reverse osmosis membranes based on polyethyleneimine and 1, 3, 5-benzoyl chloride using the spin coating technique. The selective layer has a controlled thickness, reaching 61 nm [143]. Lue et al. have fabricated composite membranes based on Nafion and graphene oxide (GO) using the spin coating technique [144]. Bouazizi et al. fabricated a composite ultrafiltration membrane using the spin coating technique. The active ultrafiltration layer was obtained from titanium powder with an estimated thickness of 18 ± 3 μm [145]. Che et al. Anhydrous proton exchange membranes (PEMs) have been fabricated from a polyvinylidene fluoride polymer, cadmium telluride nanocrystals and phosphoric acid molecules using the spin coating technique [146]. Lagdali et al. have produced a flat ceramic membrane based on natural phengite clay from Morocco. The active microfiltration layer, with a thickness of between 30.3 and 31.3 μm [147].

5.9. *Sintering method*

Dai et al. develop hydrophobic PTFE-based composite membranes deposited on ceramic substrates by dipping, then subjected to solid-state sintering at 330 °C. PTFE is dispersed with PVA, which acts as a binder, then dipped onto the ceramic substrate before drying and sintering. Solid-state sintering of PTFE/ceramic composite membranes guarantees very good hydrophobicity (133° contact angle), ideal for oil/water separations, uniform and fine pore distribution (78 nm), ensuring high-precision filtration, and a relatively low-temperature process (330 °C), reducing thermal stress. However, the formulation remains dependent on PVA to stabilize the PTFE layer, and the process is sensitive to soaking parameters (time, concentration), making optimization essential. The result is an ultra-thin (3.8 μm), high-performance membrane for ultrafiltration of polystyrene nanoparticles and emulsions containing androstenedione [148]. Jiang et al. have developed water glass (WG)-bonded SiC membranes, using a low-temperature (600 ˚C) co-sintering technique, combined with sputtering of the membrane layer onto a pre-sintered support. This method is advantageous because of its very low sintering temperature (600 ˚C), thanks to the WG which acts as a binder and flux, reducing energy costs; it guarantees superhydrophilic and superoleophobic properties under water, highly favorable to oil/water separation; and it is a consistent process for asymmetrical membranes without cracks. However, it is limited by dependence on optimal WG composition and the precise control required during spraying to avoid surface defects. The result is an average pore size of 0.25 μm, pure water permeance >2400 L/(h·m^2·bar), and an oil retention rate of 98.9% at 0.2 bar [149]. Liang et al. have fabricated SiC membranes reinforced with mullite whiskers, via low-temperature sintering facilitated by MoO_3 as an additive. The mechanism is based on dissolution-precipitation, which promotes mullite growth. This method guarantees improved mechanical strength (bending) thanks to mullite whiskers, good chemical stability against corrosive environments, and allows sintering at reduced temperatures (1350 ˚C) for SiC. However, it is limited by a still relatively high temperature compared to other techniques (600–330 ˚C) and requires precise adjustment of the MoO_3 content (optimum at 8 wt%). The result is a membrane with flexural strength of 37.01 MPa, an average pore size of 1.735 μm, open porosity of 39.12%, and excellent chemical stability [150]. Lima et al. compare conventional sintering with simultaneous co-sintering of support and membrane layers for the manufacture of SiC membranes, using a mixture of SiC, Al_2O_3, MoO_3, and pore-forming agents from walnut shells. Co-sintering has the advantage of improving interlayer adhesion while reducing the number of manufacturing steps, and the addition of MoO_3 lowers the sintering temperature. However, this method is more sensitive to variability in final properties, not least due to the effects of pore-forming agents. The results show that co-sintering achieves better overall performance, in terms of both porosity and mechanical strength, with sintering temperatures between 1250 and 1400 ˚C [151].

Santra and Kayal use air sintering at 1300 ˚C combined with low-melting additives such as WO_3, MoO_3, and TiO_2 to activate mullite crystal formation. The aim is to densify SiC at low temperatures and form strong bonds while retaining a porous structure, also using walnut shell powder as a pore-forming agent. Low-temperature sintering saves energy. Additives promote the growth of reinforcing crystals (mullite), increasing mechanical strength while maintaining adequate porosity. The approach is compatible with simple processes (dry pressing, conventional air sintering). However, the composition needs to be finely tuned, as the wrong proportion of additives or porogen can reduce performance. The massive removal of organic matter (pore-forming agent) can also induce defects if poorly controlled. The SC-W membrane (with 8% WO_3) showed a flexural strength of 40.52 MPa, a porosity of 39.2%, an average pore size of 3.52 μm, and very good chemical stability, particularly in alkaline environments [152]. J. Wang et al. have developed an ultra-low temperature (1100–1300 ˚C) oxidative sintering method for kaolin-alumina membranes, where mullite is formed in situ in a stoichiometric ratio of $3Al_2O_3$:$2SiO_2$. The support is obtained by extrusion, and sintering is carried out in a single step, co-sintering the support and the active layer. This approach has the advantage of using abundant raw materials at low cost, simplifying the manufacturing process, and offering good hydraulic performance. The addition of a porogen, such as corn starch, enables precise control of porosity. However, mechanical strength remains modest (8 MPa), the process being sensitive to the homogeneity of the extruded dough and temperature distribution. With 15% starch and sintering at 1100 ˚C, the membranes obtained have a porosity of 48% and a pure water flux of 1385 L/(h·m^2·bar), with good microfiltration capacity for dairy effluents [153]. Y. Wang et al. have proposed a method for sintering SiC membranes based on zeolite and alumina residues, at similar temperatures (1100–1300 ˚C). The process relies on in situ reactions to generate binding phases, enabling good densification while maintaining controlled porosity. In addition to its environmental advantages, the use of zeolitic wastes makes it possible to simultaneously optimize mechanical strength and porosity. However, this method remains dependent on the quality of the residues used and the dosage between the components. For a SiC: zeolite: alumina ratio of 8:1:1 sintered at 1300 ˚C, mechanical performance is very high (114.85 MPa), with a porosity of 28.9% and a water permeability of 1258 L/(h·m^2·bar), as well as excellent chemical stability in acidic and basic environments [154]. Finally, Zhou et al. have developed a sintering method combining fly ash extrusion and application of an internal or external coating based on suspensions of Al_2O_3 and ZrO_2, followed by sintering at 1200 ˚C. This approach allows effective control of pore size depending on the nature of the coating and the sintering conditions. It is simple, inexpensive, and particularly effective for gas separation applications, notably carbon dioxide capture. Internal coating improves the continuity of the active layer, but deposition quality is crucial to avoid defects, and final mechanical properties are unspecified. With a solids content of 5%–20% in the suspension, the films obtained are homogeneous and defect-free, and carbon dioxide uptake efficiency exceeds 90%, particularly with an internally applied coating [155]. Table 1 shows ceramic membrane sintering membranes, their principle, key advantages, main limitations, and performance results.

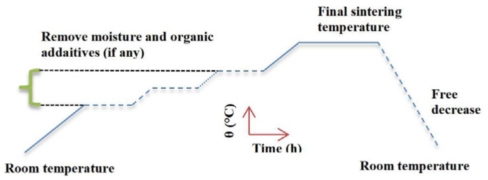

Fig. 3. Thermal treatment program.

6. Thermal treatment

6.1. Thermal program

After shaping, a thermal program is an essential step in the manufacture of porous ceramic membranes. The use of a programmable oven is necessary to adapt time and temperature [65]. The membranes are dried at room temperature for 24 h to prevent deformation and bending [156,157]. Sintering is then carried out according to a thermal program containing several temperature steps for the selective removal of additives. For example, the membrane is dried at 100 and 200 °C for 24 h to ensure maximum removal of water from the membrane and reduce thermal stress during this removal [95]. The temperatures at which the organic additives are removed depend on their thermal properties, e.g., polyvinyl alcohol (PVA) is removed at 250 °C [158]. The 350 °C temperature for burning methocel-derived amijel [75]. Remove the structural water and dehydrate HPO_4^{2-} at 400 °C for 2 h [43]. Remove the added starch at 480 ˚C for 2 h [159]. The heating rate must be low to limit thermal stresses such as cracking [89]. Fig. 3 shows a general thermal program.

6.2. Sintering temperature

Sintering temperature has an effect on average pore size and porosity. As sintering temperature increases, porosity decreases, average pore size increases, and the membrane becomes denser [45,90,93]. Several literature studies have shown the effect of sintering temperature on porosity and pore size. Nandi et al. demonstrated in their study that an increase in temperature from 850 to 1000 °C results in an increase in

Table 1
Sintering processes for ceramic membranes.

Sintering method	Principle	Advantages	Limitations	Results	Reference
Solid-sintering	Soaking + PVA/PTFE + drying/sintering at 330 °C	High hydrophobicity, fine pores (78 nm), thin layer (3.8 μm)	Dependence on binder (PVA), sensitivity to parameters	Contact angle: 133°, 78 nm pores, excellent separation	[148]
Low-temperature co-sintering	WG as flux + spraying + sintering at 600 °C	Low-cost, superhydrophilic, crack-free	Strict control of spray is required, depending on WG	Pore: 0.25 μm, permeance 2400 L/(h·m^2·bar), 98.9% oil rejection	[149]
Sintering with MoO_3	Mullite whiskers via dissolution/precipitation at 1350 °C	Good mechanical strength (37 MPa), chemical stability	Relatively high temperature	Pore size: 1.735 μm, porosity: 39.12%, corrosion-resistant	[150]
Classic sintering + low-fusion temperature additives	WO_3, MoO_3, TiO_2, $T = 1300$ °C	Low temperature, good resistance, controlled porosity	Sensitivity to composition, organic shrinkage	40.5 MPa, 39.2%, 3.52 μm, excellent chemical stability	[152]
Low-temperature oxidative sintering	Starch (porogen), $T = 1100$–1300 °C	Low cost, mono-sintering, good permeability	Low mechanical strength (8 MPa)	48% porosity, 1385 L/(h·m^2·bar), good microfiltration	[153]
Reactive sintering (zeolite+alumina)	Zeolite, Al_2O_3, $T = 1300$ °C	Very high resistance, controlled porosity, waste use	Dependence on the raw materials ratio and quality	114.85 MPa, 28.9%, 1258 L/(h·m^2·bar), good chemical resistance	[154]
Coating sintering	Al_2O_3, ZrO_2, $T = 1200$ °C	Fine pore control, over 90% carbon dioxide capture, material savings	Risk of coating defects, poorly detailed mechanical properties	Flawless film, carbon dioxide capture = 90%, best efficiency with inner coating.	[155]

average pore size from 0.55 to 0.81 μm, while porosity decreases from 42% to 33% [89]. Majouli et al. observed that porosity decreases considerably, from 42% at 1000 °C to 14% at 1080 °C. This reduction in porosity at 1080 °C is explained by the phenomenon of melting [160]. Beqqour et al. have developed a flat membrane based on pozzolan [161]. A significant decrease in porosity was observed in the temperature range between 1050 and 1100 °C, due to partial vitrification of the pozzolan particles. The decrease in porosity with increasing temperature can be explained by the improved connectivity between the particles and the increased density of the ceramic membrane [43]. Densification causes pores to close and grains to move closer together, which can be explained by the dehydroxylation of minerals containing OH groups [162].

7. Characterization techniques for ceramic membranes

The ceramic membranes produced were characterized by a number of techniques, including shrinkage, porosity, water absorption and density, mechanical strength, chemical resistance in acidic and basic media, surface morphology using scanning electron microscopy (FESEM), average pore size, and water permeability.

7.1. Shrinkage

Membrane shrinkage may be due to weight loss and densification within the heat treatment process. Shrinkage becomes more significant as sintering temperature increases. This indicates the effect of sintering temperature on shrinkage [43]. In the case of tubular membranes, the shrinkage of prepared ceramic membranes was calculated from the difference in length between green and sintered membranes, or through the difference between the diameters of flat membranes before and after thermal sintering. These measurements are taken using a caliper. Shrinkage was calculated using Eq. (1) [159,163] :

$$\text{Shrinkage} = \left(\frac{D_0 - D_1}{D_0}\right) \times 100\%, \tag{1}$$

where D_0 is the diameter or length of the green membrane and D_1 the diameter or length of the membranes after sintering.

7.2. Scanning electron microscopy (SEM) and pore size distribution (PSD)

The morphology of the membrane surface was studied using scanning electron microscopy (SEM). Analysis of the SEM images yielded results on micro-defects and small cracks existing on the membrane surface. Results were also obtained on pore distribution and surface homogeneity, as well as membrane texture [65]. Image J software version 1.53a was used to calculate the average pore size of the membrane through SEM images. It is capable of evaluating the diameter of 200 pores [75]. The calculation of the average pore size is based on Eq. (2) [161,69]:

$$d_{\text{ave}} = \left[\frac{\sum_{i=1}^{n} n_i d_i^2}{\sum_{i=1}^{n} n_i}\right]^{0,5}, \tag{2}$$

where n_i and d_i (μm) are pore number and pore diameter respectively.

7.3. Porosity, water absorption and bulk density

The apparent porosity, water absorption and bulk density of the ceramic membrane were evaluated using Archimedes' principle in accordance with international standards ASTM C373–88 [117]. Dry mass (m_{sec}) was calculated by drying the ceramic membrane in an electric oven at 150 °C for 2 h to remove moisture. It was then fully immersed in a distilled water bath and boiled for 5 h. After holding the ceramic membrane in the bath for 24 h, the wet mass (m_{h}) of the sample suspended in water was calculated. The membrane was then removed from the water, and lightly wiped with a cotton cloth to remove any traces of water from the membrane surface. The saturated mass (m_{sat}) was then calculated.

Apparent porosity, water absorption and bulk density were calculated according to Eqs. (3)–(5) respectively [48,88,126,164].

$$\text{Porosity (\%)} = \left(\frac{m_{\text{sat}} - m_{\text{sec}}}{m_{\text{sat}} - m_{\text{h}}}\right) \times 100\%, \tag{3}$$

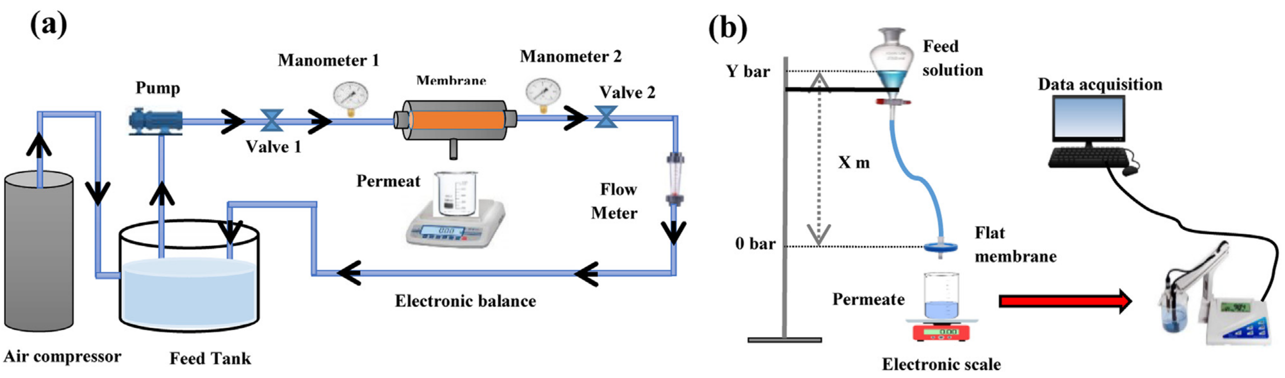

Fig. 4. Diagram of the microfiltration pilot (tangential filtration (a) and frontal filtration (b)).

$$\text{Water absorption } (\%) = \left(\frac{m_{\text{sat}} - m_{\text{sec}}}{m_{\text{sec}}}\right) \times 100\%, \tag{4}$$

$$\text{Bulk density} = \frac{m_{\text{sec}}}{m_{\text{sat}} - m_{\text{h}}}, \tag{5}$$

where m_{sat} (g), m_{sec} (g) and m_{h} (g) are the water-saturated mass of the membrane, the dry mass of the membrane and the mass of the membrane when immersed in water, respectively.

7.4. Mechanical resistance

The mechanical strength of sintered ceramic membranes was measured by the three-point bending technique, using rectangular specimens developed and sintered in the same thermal program as the membranes. Increasing sintering temperature increases mechanical strength [65]. A universal testing machine was used to carry out the tests, measuring the flexural strength of rectangular samples using a three-point test. The mechanical strength σ in MPa of the membranes was expressed by Eq. (6) [45,114].

$$\sigma = \frac{3FL}{2le^2}, \tag{6}$$

where F (N) is the force exerted at the breaking point, L (mm) is the distance between the two points of the supports, l (mm) is the specimen width and e (mm) is the specimen thickness.

7.5. Filtration test

Filtration test depends on the geometric shape of the ceramic membranes. For tubular membranes. A stainless steel laboratory pilot was used to carry out tangential filtration experiments (Fig. 4(a)). It consists of a model of the tubular membrane, a feed tank, pressure gauges to measure feed pressure at the membrane inlet and outlet, a circulation pump to produce fluid flow and an air cylinder. The pump produces a pressure ΔP (bar) regulated by adjustable valves [165,166].

Fig. 4(b) shows a stainless steel laboratory pilot using flat membranes for face filtration. The flat ceramic membrane was inserted into a suitable filtration module. The pressure ΔP was controlled through the height h between the feed level in the separatory funnel and the top surface of the flat membrane. The pressure is calculated according to Eq. (7) [87,125]:

$$\Delta P = \rho g h, \tag{7}$$

where ρ (g/cm^3) is the water density, h (cm) is the feed height and g (N/Kg) is the acceleration of gravity.

To obtain a constant flow at the start of the filtration experiment. The ceramic membrane was immersed in a bath containing distilled water for 24 h to ensure that the membrane pores were completely filled with water prior to the filtration tests [45,167].

The flux J_{w} (L/(h·m^2)) is calculated from the variation of the permeate volume V (L) in time t (h) at specific pressures by applying Eq. (8), and the permeability L_{p} (L/(h·m^2·bar)) can be obtained by calculating the variation of the flux J_{w} with respect to the transmembrane pressure ΔP (bar) based on Darcy's law (Eq. (9)) [57,168,169].

$$J_{\text{w}} = \frac{V}{S\Delta t}, \tag{8}$$

$$L_{\text{p}} = \frac{J_{\text{w}}}{\Delta P}, \tag{9}$$

where S (m^2) is the membrane filtration area.

7.6. Chemical resistance

The chemical resistance of the engineered membranes was measured in extreme acidic and basic media. Sodium hydroxide (NaOH) and hydrochloric acid (HCl) were used to prepare the strongly acidic and strongly basic solutions [147]. The ceramic membranes were dried in an electric oven to remove moisture. The dry mass m_1 (g) before immersion was then calculated. They were then immersed in beakers containing 100 mL of acidic and basic solutions at room temperature for several days. The ceramic membranes were then washed thoroughly with distilled water and dried in an electric oven. The m_2 mass (g) after immersion was calculated. The weight loss W_{L} (%) was expressed by Eq. (10) [64,170].

$$\text{Weight loss } (\%) = \left(\frac{m_1 - m_2}{m_1}\right) \times 100\%\ . \tag{10}$$

7.7. Rejection rate

Membrane performance was estimated by calculating the rejection retention rate. The removal efficiency is calculated by Eq. (11) [44,171].

$$R\ (\%) = \left(\frac{C_{\text{i}} - C_{\text{f}}}{C_{\text{f}}}\right) \times 100\%, \tag{11}$$

with C_{i} and C_{f} representing the physicochemical parameters before and after filtration.

8. Membranes fouling

8.1. Fouling mechanism

The time-dependent decrease in flux during constant-pressure filtration can be identified by several clogging mechanisms. Hermia's models have been tested, in particular the complete pore blocking model (Eq. (12)), the standard pore blocking model (Eq. (13)), the intermediate pore blocking model (Eq. (14)) and the cake filtration model (Eq. (15)) [172,173]. Fig.5 explains these models graphically [174].

$$\ln(J)^{-1} = \ln(J_0^{-1}) + K_{\text{b}}t, \tag{12}$$

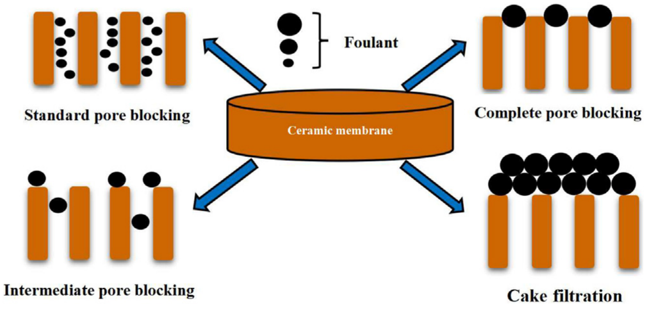

Fig.5. Different fouling mechanisms used during membrane filtration.

$$J^{-0.5} = J_0^{-0.5} + K_s t, \quad (13)$$

$$J^{-1} = J_0^{-1} + K_i t, \quad (14)$$

$$J^{-2} = J_0^{-2} + K_c t, \quad (15)$$

in which J represents the permeate flux, J_0 represents the initial flux, k_b, k_s, K_i and k_c represent the slopes and t represents the filtration time.

8.2. Antifouling study

The membranes manufactured were tested at room temperature and under pressure to determine their antifouling performance. Firstly, distilled water permeate flux (J_{w0}) had to be measured with a fresh membrane. Next, permeate flux (J_{wp}) was measured after filtration of the retentate through the membrane. The membrane was then rinsed thoroughly with distilled water. After washing, the permeate flux (J_{w1}) of distilled water was measured. The antifouling characteristics of the membrane were measured including FRR (flux recovery rate), TFR (total flux decline rate), RFR (reversible flux decline rate), and IFR (irreversible flux decline rate), using Eqs. (16)–(19) [68,175].

$$\text{FRR }(\%) = \left(\frac{J\text{w}_1}{J\text{w}_0}\right) \times 100\%, \quad (16)$$

$$\text{TFR }(\%) = \left(\frac{J\text{w}_0 - J\text{w}_\text{p}}{J\text{w}_0}\right) \times 100\%, \quad (17)$$

$$\text{RFR }(\%) = \left(\frac{J\text{w}_1 - J_\text{p}}{J\text{w}_0}\right) \times 100\%, \quad (18)$$

$$\text{IFR }(\%) = \left(\frac{J\text{w}_0 - J\text{w}_1}{J\text{w}_0}\right) \times 100\% . \quad (19)$$

9. Industrial applications of ceramic membranes

The wide range of applications for low-cost ceramic membranes based on natural materials makes them comparable to commercial membranes. Low-cost ceramic membranes have been applied to a variety of applications, including real or synthetic wastewater treatment, oil and heavy metal removal in various industrial sectors (Fig. 6).

9.1. Oil-water emulsion wastewater treatment

The rapid growth of various industries, such as oil refineries, petrochemicals, metallurgy and transport, is constantly producing very large quantities of oil-in-water emulsions. These emulsions contain high levels of oils and fats, plus other additional pollutants [176,177]. These industries produce wastewater with oil concentrations ranging from 50 to 1000 mg/L [47]. Discharge of significant volumes of oily wastewater poses risks to the aquatic environment [178]. In recent years, membrane technology has provided an effective solution to these problems. Today, industrial sectors are increasingly interested in membrane technology [177]. This separation technology has been widely used because of its advantages, such as its very high hydrocarbon removal performance, its lower cost than conventional technologies and its use without chemical additives [179,180]. Table 2 show the performance obtained in some scientific studies on the separation of oil-water emulsions. These results show that low-cost ceramic membranes achieved excellent oil rejection rates of over 95%.

The advantages of using ceramic membranes in wastewater treatment of oil-water emulsions are that they enable efficient separation of oil and water even in fine emulsions, resist fouling by oily compounds thanks to their inorganic surface, and retain their performance after several chemical cleaning cycles.

9.2. Textile industry wastewater treatment

The growth of the textile industry has been very significant, and it plays a key role in the economic development of various countries [181]. In addition, the growth of industrial activities is putting great pressure on the planet's water resources, due to the high water requirements at all stages of the process. Indeed, they produce large quantities of pollutants, namely chemical oxygen demand (COD), heavy metals, dyes, chemicals, fats and oils, biological oxygen demand (BOD) and mineral salts, which are discharged into the water cycle, threatening the fragile ecosystems that ensure the healthy development of life on our planet [67,182,183]. The volumes of wastewater produced by this industry range from 2 to 180 liters per kilogram of textiles, depending on the processes employed and the type of materials used (wool, cotton, synthetic fibers, etc.) [184].The biggest problem for the environment is the massive presence of colorants, which are difficult to biodegrade and cannot be eliminated efficiently, making them difficult to dispose of [185]. Several textile wastewater treatment methods, such as the adsorption method, the coagulation method, the membrane filtration method, the advanced oxidation method and the activated sludge biological treatment method, are required [186,187]. Membrane separation techniques have proven their effectiveness in water treatment, recovery and desalination [184]. Bousbih et al. have developed ceramic ultrafiltration membranes from natural Tunisian kaolin clay, specifically designed for the treatment of textile wastewater, targeting color removal, chemical oxygen demand and turbidity [188]. In addition, several researchers have used low-cost ceramic membranes to treat wastewater from the textile industry, with remarkable results in terms of turbidity and COD reduction (Table 3).

The advantages of using ceramic membranes in the treatment of industrial textile wastewater are that they remove dyes and surfactants efficiently and at low cost, and are highly chemically stable in the face of the oxidizing agents used in this industry.

9.3. Tannery industries wastewater treatment

The leather tanning industry is one of the relatively large manufacturing sectors in certain developing countries [189]. The tanning industry is one of the most polluting. It uses large quantities of fresh water in its production process and therefore discharges this water into the natural environment in the form of hazardous wastewater. The industry generally discharges 30 to 35 m^3 of wastewater for every ton of raw hide. Tannery wastewater contains large quantities of organic matter, various coloring substances, chromium, nitrogenous matter, surfactants and grease, and its presence in the environment can have harmful effects on the ecosystem [190–192]. High levels of pollutants and a wide range of compositions require physical, physico-chemical and biological treatment [67]. For this reason, the development of low-cost ceramic membranes based on natural materials such as clay and waste has made great strides in recent years [193]. In the field of scientific research,

Table 2
Wastewater treatment using various low-cost ceramic membranes in the oil-water.

Membrane material	Membrane configuration	Membrane type	Sintering temperature (°C)	Porosity (%)	Pore size (μm)	water permeability (L/(h·m^2·bar))	Mechanical strength (MPa)	Oil Concentration in feed (mg/L)	Applied pressure	Rejection (%)	Reference
Fly ash / titanium dioxide	Flat	MF	1100	48.00	2.280	0.63×10^{-8} $m^3/(m^2 \cdot s \cdot Pa)$	13.82	200	69 kPa	99.20	[47]
Ball clay, kaolin, feldspar, quartz, pyrophyllite and calcium carbonate	Tubular	MF	950	53.00	0.309	5.93×10^7 m/(s·kPa)	12.00	100 ppm	69 kPa	99.98	[99]
Clay, talc and alumina	Tubular	MF	1025	36.50	0.600	101.90	25.30	200	3 bar	99.91	[176]
Locally clays	Tubular	MF	950	50.00	0.339	7.35×10^{-7} $m^3/(m^2 \cdot s \cdot kPa)$	12.00	100	68 kPa	99.88	[177]
Ffly ash/ kaolin	Flat	–	1250	37.00	320 nm	3650.00	50.70	400 ppm	0.1 MPa	98.50	[195]
Waste attapulgite (WAT)/α-Al_2O_3	Flat	–	1100	41.60	0.400	1235.00	37.20	1000	0.2 bar	99.08	[196]
Clay/ TiO_2 Composite membrane	Flat	MF	support 950 membrane 400	45.57 ± 0.65 43.32 ± 0.35	0.980 ± 0.021 1.010 ± 0.036	–	–	200	69–207 kPa	99.56	[197]
Tunisian natural clay/Cellulose	Tubular	MF	850	40.00	2.500 and 0.070	8.5 L/(h·m^3)	6.50	–	2 bar	50.00	[198]
Coal fly ash/natural bauxite/WO_3	Flat	MF	1400	51.90 ± 0.30	0.480	–	68.70 ± 6.10	250	50–150 KPa	96.00–99.00	[199]
Fly ash/Al_2O_3	Flat	MF	1050	–	100 nm	450.00	–	200	0.05 MPa	99.2.00	[200]
Coal gangue/$Al(OH)_3$	Flat	MF	1400	47.21 ± 0.48	185.3 nm	–	34.00 ± 2.50	250	0.1 MPa	97.00	[201]
Coal	Tubular	MF	900	42.15	1.000	450.7 L/(m^2·h)	–	120 250 400	0.10 MPa	97.80 98.90 98.60	[202]
Kaolin, Quartz, Calcium and Carbonate	Flat	MF	900	30.00	1.300	–	34.00	250	69 kPa	850	[203]
China clay, $AlF_3 \cdot 3H_2O$ and Al_2O_3	Flat	MF	1400	64.00	0.300	1031.00	43.00	200 500 1000	2 bar	960 96.40 97.60	[204]
Kaolin, Quartz, calcium carbonate, sodium carbonate, boric acid, and sodium metasilicate	Flat	MF	900	37.40	2.160	–	–	400	207 kPa	98.52	[205]

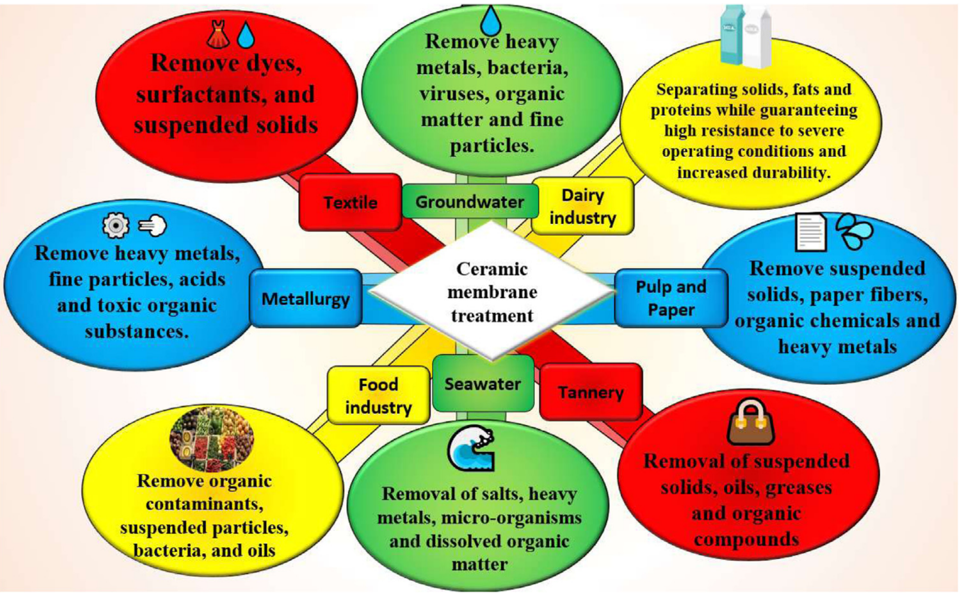

Fig.6. The role of ceramic membranes in the treatment of various industrial effluents.

membrane filtration relies on a pressure difference to allow wastewater to pass through a membrane whose pores, of a precise size, retain pollutants [194]. Particular interest has been shown in membrane technologies, whose cost continues to fall while the range of applications continues to expand. Their use in the leather industry offers a significant economic advantage, particularly for chrome recovery [191]. In addition, a few studies have used low-cost ceramic membranes to treat wastewater from the tanning industry, and have succeeded in achieving significant turbidity and COD discharges (Table 4).

The advantages of using ceramic membranes in the treatment of industrial wastewater from tanneries are that they can withstand very acidic and very basic media, effectively separate fats, solids and heavy metals, and can be regenerated by powerful chemical cleaning processes without loss of performance.

9.4. Dairy industry wastewater treatment

The dairy sector is one of the world's basic industries. Dairy products include the processing of raw milk into yoghurt, cheese, powder, ice creams, various types of desserts, etc. Dairy production is one of the activities that generate the majority of industrial effluents in Europe [214,215]. The processing of one liter of milk by the dairy industry is responsible for the production of around 2.5 liters of wastewater [172]. Wastewater comes from the cleaning of production equipment and various analyses carried out by quality control laboratories. The main constituents of this water are lactose, proteins, fats, various cleaning products and certain mineral salts [216]. Every year, around 47% of the 115 million tonnes of whey produced worldwide are discharged into the natural environment. This creates serious pollution problems, as whey is a highly concentrated organic pollutant, with very high levels of BOD_5 and COD, varying between 40000 and 60000 mg/L and between 50000 and 80000 mg/L respectively [217]. These effluents can cause major problems related to the organic overloading of local municipal wastewater treatment systems [218]. The various ways of treating these effluents have therefore attracted increasing attention [215]. A number of researchers have investigated the treatment of dairy wastewater using low-cost ceramic membranes. Deka et al. developed a tubular ceramic membrane made from low-cost clay materials for the treatment of dairy wastewater. This membrane achieved 52.08% COD removal at a very low pressure of 13.8 kPa [219]. El Machtani Idrissi et al. developed a ceramic microfiltration membrane from kaolinite and perlite. This membrane, with an average pore diameter of 1.25 μm and a permeability of 1779 L/(h·m^2·bar), reduces COD by up to 75.44% at a pressure of 0.12 bar [206]. Hatimi et al. have fabricated an economical microfiltration membrane from natural clay and pyrrhotite ash solid waste. This membrane has a porosity of 34% and a permeability of 22.88×10^{-7} m^3/(h·m^2·kPa). It removes 100% of turbidity at a pressure of 60 kPa [84]. Vinoth Kumar et al. have developed a tubular ceramic membrane from natural clay materials. This membrane has a pore size of 0.309 μm, a water permeability of 5.93×10^{-7} m^3/(m^2·s·kPa) and a porosity of 53%. It achieved a maximum COD reduction of 91% at an applied pressure of 207 kPa [172] . Al-Shammari et al. achieved a 92.5% reduction in COD using a system combining biological treatment, powdered activated carbon (PAC) and a submerged membrane microfiltration system (CMF-S) [220].

The advantages of using ceramic membranes to treat wastewater from the dairy industry are that they retain fats, proteins and complex sugars, are resistant to clogging caused by organic loads, and significantly reduce the chemical oxygen demand in the wastewater.

9.5. Food industry wastewater treatment

The food industry is one of the biggest producers of large quantities of wastewater containing organic and inorganic contaminants. Inexpensive ceramic membranes are one of the most promising solutions for treating this water, thanks to their ability to remove organic matter, oils, greases and suspended solids. Ceramic membranes are robust and durable, making them a good choice for food plants requiring long-lasting water treatment systems. In this industry's wastewater treatment, ceramic membranes are used to improve filtration and separation of contaminants, capturing both large and small particles, thus improving the quality of treated water. These membranes can operate under a wide range of environmental conditions, such as high temperatures and variable pH levels, making them suitable for many applications in the treatment of wastewater from different food industries. What's more, low-cost ceramic membranes represent a cost-effective option for plants looking to minimize water treatment costs while protecting the environment. The use of these membranes reduces the amount of chemicals consumed in traditional treatment processes such as flocculation and coagulation, thus minimizing the impact of these processes on the environment. The application of ceramic membranes in the treatment of food industry wastewater represents a major technological advance,

Table 3

Wastewater treatment in the textile industry using a variety of low-cost ceramic membranes.

Membrane material	Membrane configuration	Membrane type	Sintering temperature (°C)	Porosity (%)	Pore size (µm)	Permeability (L/(h·m^2·bar))	Mechanical strength (MPa)	Applied pressure (bar)	COD rejection (%)	Turbidity rejection (%)	Reference
Local Moroccan magnesite	Flat	MF	1100	48.15	1.12	922.0	6.1	0.12	69.70	99.90	[44]
Alumina membrane (commercial ceramic membrane)	Tubular	MF	–	–	0.20	1022.0	–	1.00	65.00–70.00	89.00–94.00	[94]
Coal fly-ash	Tubular	MF	1125	51.00	0.25	475.0	19.5	1.00	75.00	–	[114]
Tunisian natural kaolin	Tubular	UF	1000	–	35 nm	21.2	13.0	5.00	Raw effluent 80 Pretreated effluent 93	Raw effluent 98 Pretreated effluent 100	[188]
kaolinite/ perlite	Flat	MF	1050	30.28	1.25	1779.0	–	0.12	–	97.00	[206]
Phosphates	tubular	UF	900	39.00	11 nm	90.0	14.4	5.00	90.00	99.00	[207]
Carbon	Tubular	MF	700	38.00	0.60	100.0	–	3.00	57.00	90.00	[208]
Zeolite/ Smectite	Tubular	UF	900	–	18 nm	80.0	–	3.00	87.40	–	[209]
Carbon	Tubular	MF	700	34.00 37.00	0.50 0.80	4.5 150.0	–	1.00	48.00 59.00	89.00 89.00	[210]
clay/banana peels	Flat	MF	1100	40.30	5.50	550.0	19.2	1.50	49.62	96.10	[211]
phosphate/ kaolinite	Flat	MF	1000	41.30	0.35	1045.0	40.2	0.12	74.00	98.99	[212]

Table 4

Wastewater treatment in the tannery industry by means of various low-cost ceramic membranes.

Membrane material	Membrane configuration	Membrane type	Sintering temperature (°C)	Porosity (%)	Pore size (µm)	Permeability (L/(h·m^2·bar))	Mechanical strength (MPa)	Applied pressure (bar)	COD Rejection (%)	Turbidity Rejection (%)	Reference
Red clay/ Natural phosphate	Flat	MF	1100	28.11	2.50	928.00	17.50	0.14	–	99.80	[59]
Pyrrhotite ash/ Clay	Flat	MF	1000	34.00	–	22.88×10^{-7} m^3/(h·m^2·kPa)	27.42	60 KPa	–	96.00	[84]
Moroccan Perlite	Tubular	MF	1000	42.00	0.27	815.00	–	1.00	50.00–54.00	98.00	[94]
Alumina membrane (commercial ceramic membrane)	Tubular	MF	–	–	0.20	1022.00	–	1.00	58.00–65.00	98.00–99.00	
Natural perlite	Flat	MF	950	52.11	1.70	1433.46	21.68	0.12	–	96.00	[159]
Pozzolan / Micronized phosphate	Flat	MF	1050	32.07	1.33	1732.50	15.69	0.12	–	97.00	[161]
Red clay/ tea waste	Flat	MF	1100	39.15	2.80	1249.00	14.81	0.14	76.43	99.16	[194]
Clay/Banana peels	Flat	MF	1100	40.30	5.50	550.00	19.20	1.50	50.26	95.95	[211]
Natural Moroccan bentonite	Flat	MF	950	32.12	1.70	520.00	22.00	0.12	–	94.00–99.00	[213]

enabling efficient and sustainable purification. The use of these membranes is based on their ability to ensure precise separation of contaminants while maintaining high filtration rates and increased resistance to clogging. Zhong et al. investigate the treatment of oily effluents from refinery processes using a combination of flocculation and microfiltration on zirconia membranes. The results show a significant reduction in organic load and oil content, thanks in particular to optimal pretreatment to improve permeate flow and limit membrane fouling [221]. In a similar vein, Tawalbeh et al. highlight the value of ceramic membranes as a pretreatment for oily water prior to desalination, emphasizing their separation efficiency and operational stability. The focus is on operating parameters such as transmembrane pressure and crossflow velocity, which directly influence separation performance [222]. Tanudjaja et al. present a practical perspective on membrane separation applied to oily effluents from various industries, comparing the performance of membranes to conventional techniques such as dissolved air flotation and coagulation. Economic analysis and clogging mitigation strategies are developed, reinforcing the interest in ceramic membranes [223]. Šereš et al. focus on the treatment of vegetable oil refinery effluent using alumina membranes, confirming their potential for reducing chemical oxygen demand and turbidity. The use of response surface methodology enables operational parameters to be optimized for a cost-effective process [224]. Furthermore, Kumar et al. explore a novel approach using a low-cost tubular ceramic membrane for dairy wastewater treatment. Results indicate a strong reduction in organic load (91% decrease in chemical oxygen demand) with a clogging pattern dominated by the formation of a filter cake [172]. Regarding the fishing industry, Kuca and Szaniawska highlight the potential of ceramic membranes in the treatment of saline effluents from fish processing. Protein rejection reaches 81%, and the reduction in organic loads is significant, favoring brine reuse [225]. Membrane clogging represents a major challenge in industrial applications. Poerio et al. analyzed clogging mechanisms in the microfiltration of olive oil mill effluents, identifying cake formation as the main factor reducing flux [226]. Similarly, Mulinari et al. are exploring an innovative alumina membrane modification strategy using polydopamine-assisted lipase immobilization to improve resistance to clogging [227]. Pérez-Gálvez et al. focus on the operation and cleaning of membranes in the filtration of fish pressing juices, highlighting a three-stage cleaning protocol (alkaline, acid, disinfection) to restore the initial efficiency of the membranes [228]. Padaki et al. look at technological advances in the design and functionalization of ceramic membranes. Nanoparticle integration, interfacial polymerization and surface grafting are promising techniques for improving membrane selectivity and durability [229]. Finally, Mouiya et al. discuss the production of low-cost ceramic membranes, a strategic approach aimed at making these technologies more accessible to agri-food industries. The use of natural Moroccan materials such as Safi clay and Youssoufia phosphate in the manufacture of microfiltration membranes proves the effectiveness of this approach for desalination and industrial effluent treatment applications [59]. As a result, ceramic membranes represent a high-performance, sustainable alternative for wastewater treatment in the food industry. Their ability to handle complex effluents, resistance to extreme conditions and clogging mitigation strategies pave the way for wider adoption of these technologies. However, more needs to be done to reduce manufacturing costs and further improve membrane durability.

The advantages of using ceramic membranes in wastewater treatment in the food industry are that they can withstand the treatment conditions of organic-rich food waste, they are effective in removing fats, oils and solids, and their low cost means that they can be used in large-scale treatment systems.

9.6. Metallurgy industry wastewater treatment

The metallurgical industry produces large volumes of wastewater containing heavy metals such as zinc, lead, and cadmium, as well as organic matter and dissolved metals. Inexpensive ceramic membranes play an important role in the treatment of such water, thanks to their ability to remove toxic substances and heavy metals [230]. These membranes effectively separate heavy particles from the water, which are removed by the filtration process. The importance of using ceramic membranes in the metallurgical industry lies in the fact that they are highly resistant to corrosion and penetration and therefore remain effective for long periods without the need for frequent maintenance [231]. Ceramic membranes can effectively remove solid contaminants and heavy metals, reducing the concentration of toxic substances in contaminated water [232]. In addition to the removal of heavy pollutants, ceramic membranes can be used in secondary treatment technologies such as desalination, making them versatile tools for the treatment of industrial wastewater from the metallurgical industry [233].

The advantages of using ceramic membranes in wastewater treatment in the metallurgical industry are that they withstand corrosive environments rich in heavy metals, effectively separate metal particles and inorganic compounds, and retain a long service life despite the aggressive nature of the effluent.

9.7. Paper and pulp industry wastewater treatment

The paper and pulp industry produces large quantities of wastewater containing organic and inorganic pollutants such as chemicals used in the bleaching process, as well as fine solids [234]. Inexpensive ceramic membranes play a major role in the treatment of these waters thanks to their ability to remove organic substances, toxic chemicals, and suspended solids [52]. Ceramic membranes are capable of treating the acidic or alkaline water that characterizes certain paper-making processes, making them an ideal choice for treating contaminated water in this field [235]. Ceramic membranes can easily remove toxins and organic matter, minimizing the industry's impact on the environment [236].

The advantages of using ceramic membranes for wastewater treatment in the paper industry are that they retain fibers, colloids and organic matter, are less prone to clogging by solid loads, and allow continuous treatment with little maintenance.

9.8. Seawater treatment

Seawater desalination is a vital application for low-cost ceramic membranes. Seawater suffers from high salinity and the presence of numerous contaminants such as bacteria, viruses and heavy metals. Ceramic membranes are a good choice for seawater filtration, used in reverse osmosis or vacuum filtration to separate dissolved salts and metals. Ceramic membranes can remove salts and other suspended substances, improving seawater quality and making it suitable for consumption or industrial use. These membranes are a sustainable and less expensive solution for desalination, as they do not require high operating costs compared with other systems such as solar or gas desalination. Achiou et al. have developed a tubular microfiltration membrane based on natural pozzolan, an abundant and inexpensive material. Using an extrusion technique followed by sintering at 950 °C, they obtained a homogeneous structure with controlled porosity and high permeability (1444.7 $L/(h{\cdot}m^2{\cdot}bar)$). The use of pozzolan, combined with organic additives and water, has enabled the development of an effective membrane for the pre-treatment of seawater prior to reverse osmosis. These results demonstrate the potential of local natural resources to reduce desalination costs, while maintaining competitive performance [158]. Altmann et al. conducted a pilot study on the effectiveness of ceramic ultrafiltration membranes (CUF) as a pretreatment for reverse osmosis (SWRO) in the Gulf region. Faced with extreme marine conditions and harmful algal blooms, they demonstrated that CUFs outperformed polymeric membranes in terms of permeate quality and operational resilience. At the height of the blooming season, CUFs operated at full capacity, while conventional MF/UF systems experienced a 30%–40% reduction in capacity. In addition, CUFs removed up to five times more dissolved organic carbon (DOC) and 1.5 times more transparent exopolymeric particles (TEP), underlining their suitability for stable desalinated water production [237]. Bae et al. explored a hybrid approach combining seawater desalination and carbon dioxide capture using an electrochemical system based on a seawater battery. Thanks to a superionic ceramic membrane, this device enabled a significant reduction in dissolved solids in seawater (from 34000 to 7000 ppm), while capturing atmospheric CO_2 via carbonation reactions. This dual functionality represents a major step forward in simultaneously addressing the challenges of freshwater scarcity and climate change, although the industrial feasibility of this concept still requires in-depth studies [238]. Belgada et al. have developed a ceramic microfiltration membrane derived from rock phosphate and optimized by sintering at 1000 °C. The membrane has a permeability of 697 L/(h·m^2·bar), a porosity of 25.6% and an average pore size of 0.26 µm. Applied to the pre-treatment of raw seawater, it showed a notable 73% reduction in total organic carbon (TOC) and a 98% reduction in turbidity. In addition, its Suspended Solids Density Index (SDI) dropped from 5.41 to 3.25, providing better protection for reverse osmosis membranes. Simple cleaning recovered 74% of the initial flow, demonstrating the durability and ease of maintenance of this technology [43]. Bindels et al. have economically evaluated the coupling of reverse osmosis (RO) with air gap membrane distillation (AGMD) for the treatment of saline discharges. Laboratory tests revealed a tendency for membranes to clog, necessitating appropriate pre-treatment. By integrating antiscalants and various filtration combinations (UF, NF), the study identified an optimal scenario where the addition of an antiscalant enabled a recovery rate of 84.59% with a water cost of 0.633 USD/m^3. These results underline the need for optimization strategies to make desalination more economical and sustainable [239]. Cui et al. studied the influence of filtration parameters on ceramic membranes used in reverse osmosis pretreatment. They found that pore size did not significantly affect permeation flux, while coagulation method played a key role. Under pilot conditions, the ceramic membrane maintained a stable flow of 150 L/(m^2·h) with turbidity and SDI15 in line with RO requirements. These observations confirm the effectiveness of ceramic membranes in producing high-quality pre-treated water [240]. Cui et al. investigated the effect of crossflow velocity on the critical flux of ceramic membranes. The study revealed that this velocity significantly influenced flux only in the transition zone between laminar and turbulent regimes. The membrane maintained a flow of 150 L/(m^2·h) over 2922.4 h without the need for chemical cleaning, demonstrating its excellent stability and low fouling, which reinforces its attractiveness for the pre-treatment of seawater prior to reverse osmosis [241]. Cui et al. conducted a pilot study on the pretreatment of seawater from Tianjin Bohai Bay using a ceramic membrane. Optimization of the coagulation process improved permeate quality, guaranteeing low turbidity and an SDI suitable for reverse osmosis. In addition, the membrane demonstrated exceptional robustness in winter conditions (3–6 °C), suggesting its suitability for operation in a variety of climatic environments [242]. Gazagnes et al. explored the use of hydrophobic ceramic membranes for air gap membrane distillation (AGMD) in seawater desalination. Chemically modified zirconia, alumina and alumino-silicate membranes offered rejection rates in excess of 95%, with zirconia (50 nm) showing the best performance. This approach improves the thermal and chemical resistance of the membranes, while reducing the energy consumption of the process, making AGMD a promising alternative to conventional desalination methods [243]. Hamad et al. examined the advantages of ceramic membranes in microfiltration and ultrafiltration as a pretreatment prior to reverse osmosis. Their enhanced chemical resistance enables more aggressive washing and more stable operation than polymeric membranes. Lower SDI (Suspended Solids Density Index) makes RO membranes easier to operate, extending their service life and improving desalination efficiency [244]. Hubadillah et al. explored the use of green silica-based ceramic membranes for seawater desalination via direct contact membrane distillation (DCMD). Their study demonstrated that hollow-fiber membranes (CHFMs) made from treated rice stalk ash not only performed well in terms of permeate flux (38.2 kg/(m^2·h)), but also offered excellent salt rejection capacity (99.9%). These membranes were surface-modified to become hydrophobic by grafting with a fluoroalkylsilane agent, resulting in a lotus leaf structure with a contact angle greater than 150°, thus improving their efficiency under conditions of high temperature and varying NaCl concentrations. This approach has opened up prospects for sustainable solutions in seawater desalination, using materials of renewable origin [245]. Kang et al. investigated the application of ceramic membranes in microfiltration as a preliminary step for reverse osmosis (RO) seawater desalination. They compared the performance of ceramic membranes with and without coagulant addition in terms of permeate quality and transmembrane pressure (TMP). The results showed that the addition of coagulant significantly reduced the increase in TMP, indicating an attenuation of membrane clogging. In addition, filtration systems with coagulation showed significantly improved dissolved organic matter (DOC) rejection rates, turbidity and SDI_{15} parameters, underlining the potential of ceramic membranes as pretreatment in reverse osmosis desalination processes, particularly for marine waters containing particulate matter and organic substances [246]. Ma et al. investigated a photo-piezoelectric decoupling technology for seawater splitting, focusing on optimizing the performance of perovskite-based ceramic membranes. Their innovative approach combined photocatalysis and piezoelectric effects to improve charge separation efficiency and accelerate surface redox reactions. Using protonated La_2NiO_4 perovskite ceramic membranes, the researchers achieved very high hydrogen production rates (7750.41 µmol/(m^2·h)) under photo-piezoelectric conditions, highlighting a promising potential for hydrogen production from seawater via a combined catalytic approach [247]. Omar et al. developed superhydrophobic ceramic membranes for seawater desalination by membrane distillation. Using a two-stage method, the researchers fabricated composite membranes based on mullite and stainless steel, characterized by a flake-like structure and high angular contact (>155°). In tests, these membranes showed exceptional performance, with a salt rejection rate close to 99.91% and a permeate flux of 24.3 L/(m^2·h). These results confirm that superhydrophobic ceramic membranes have great potential for industrial applications in harsh desalination environments, thanks in particular to their non-stick properties and robustness [248]. Pérez et al. evaluated the performance of ceramic membranes for filtering seawater contaminated with okadic acid and heavy metals. Their study showed that ultrafiltration (UF) membranes were more effective than microfiltration (MF) in reducing turbidity, alkalinity, chemical oxygen demand (DOC), and chlorophyll. In particular, the membranes showed significant rejection of okadic acid, a major toxicant from algae, and metal ions such as Pb^{2+}, depending on pH and transmembrane pressure conditions. This research highlights the potential of ceramic membranes for seawater filtration applications in specific environmental contexts, including protection against marine pollution [249]. Perez-Moreno et al. investigated the use of ceramic membranes for seawater desalination along Mexico's Pacific coast, a region facing water supply challenges due to its semi-arid nature. They demonstrated that nano-filtration (NF) modified ceramic membranes were not only more chemically and mechanically resistant than polymer membranes, but also offered greater longevity and reduced environmental impact. The results showed that these NF membranes could be used effectively for the reduction of specific ions in seawater, offering a potential long-term solution to the region's water supply problems [250]. Rakcho et al. presented an innovative method for the manufacture of low-cost ceramic membranes for wastewater and seawater treatment, using Moroccan red clay and tea waste as porosification agents. Their study highlighted the ability of these membranes to effectively remove turbidity and suspended solids in tannery wastewater, while offering exceptional filtration performance for seawater. Results showed permeability rates of 1249 L/(h·m^2·bar) and turbidity removal efficiencies of up to 99.76%, underlining the potential of these ceramic membranes as an economical and effective alternative for water treatment [194]. Samhari et al. produced a flat microfiltration ceramic membrane from natural kaolinite clay and corn starch for the pretreatment of seawater for the desalination and clarification of agri-food wastewater. Their study showed that the addition of 10% starch by weight optimized the mechanical properties and permeability of the membrane, which showed turbidity rejection of 73% for raw seawater and 99% for agri-food effluent. These results indicate that kaolinite clay-based ceramic membranes can be used effectively in water treatment, while offering a sustainable, low-cost solution for pre-treatment in desalination systems [251]. In the study by Twibi et al., a hydrophobic mullite hollow fiber ceramic membrane (Hy-MHFM) was developed for seawater desalination via direct contact membrane distillation (DCMD). Researchers fabricated the membrane by phase inversion, followed by fluoroalkyl silane (FAS) grafting. The membrane showed exceptional salt rejection performance, reaching 99.99% at a feed temperature of 60 °C and a permeate temperature of 10 °C, with a flux of 22.51 kg/m^2/h. However, performance decreased with increasing feedwater salt concentration, underlining the importance of temperature in maintaining optimum flux [252]. Xavier et al. studied the use of steel slag in the manufacture of ceramic membranes for seawater pretreatment. Steel slag, rich in metal oxides, was used to manufacture ceramic microfiltration membranes, with varying concentrations (5%, 10%, and 20%). Results showed a significant improvement in hydraulic permeability, particularly with 20% slag, reaching 5263.2 kg/(m^2·h·bar). The 20% slag membrane also showed a turbidity reduction efficiency of 97.35%, making it a promising choice for the pre-treatment of seawater prior to reverse osmosis [48]. In the study by Xavier et al., the effect of flocculation and temperature on microfiltration for seawater pretreatment was analyzed. The use of flocculants such as ferrous sulfate and anionic polyacrylamide considerably improved the microfiltration process, particularly at 40 °C. The hydraulic permeability of the membranes increased with temperature, reaching 11600 L/(h·m^2·bar) at 60 °C. This work demonstrated that the combination of flocculation and ceramic microfiltration improves the efficiency of seawater pretreatment and reduces membrane fouling [253]. Xu et al. investigated the performance of a zirconium dioxide ceramic membrane for the pre-treatment of seawater prior to desalination by reverse osmosis. The researchers examined the influence of various operational parameters, such as transverse flow velocity, temperature, transmembrane pressure and seawater pH, on membrane flux and rejection. Results showed high permeate flux (420–450 L/(h·m^2)) and turbidity and COD_{Mn} rejection in excess of 99%. The tests also identified the main resistances over time, highlighting the importance of concentration polarization and reversible fouling [254]. In the study by Xu et al., anti-fouling approaches were explored to improve the performance of ceramic ultrafiltration membranes. Treatment with ferrous sulfate and polyacrylamide alcohol showed positive results, particularly for DOC removal. In addition, ceramic membranes could be effectively cleaned after fouling with NaClO solutions, enabling rapid recovery of performance. The study concluded that optimization of cleaning and backwash conditions was crucial to maximize the efficiency of these membranes in seawater pretreatment [255]. The study by Zhang et al. developed silicon nitride hollow membranes for seawater desalination via vacuum membrane distillation (VMD) and direct contact membrane distillation (DCMD). The membranes showed excellent performance, with a salt rejection rate in excess of 99%, as well as long-term stability in terms of salt flux and rejection. The application of these membranes for seawater desalination was deemed promising, with an optimum combination of flux and mechanical strength, ideal for industrial applications [256]. Zhou et al. explored the fabrication of a FAU zeolite membrane for pervaporation desalination. The membrane, manufactured without seeds, showed excellent ion rejection with a rejection rate of over 99.8% for ions present in seawater. Results showed that the membrane's permeability increased with temperature, leading to improved desalination performance. This study demonstrated the efficiency of zeolite membranes for seawater desalination, even at high salt concentrations [257]. In the study by Zhu et al., an MFI zeolite membrane was used for seawater desalination, with high rejection of major ions, although rejection decreased at higher temperatures. Selective diffusion of ions was observed, and the membrane structure remained stable after 180 d of exposure to seawater. This study highlights the importance of temperature on the performance of zeolite membranes, a crucial factor for large-scale desalination [258]. In the study by Lagdali et al. a flat membrane based on natural phengite clay was used for seawater pretreatment. Turbidity levels were significantly reduced by using the produced membrane, reaching 98.7% for RSW1 and 96.8% for RSW2 [147].

The advantages of using ceramic membranes in seawater treatment are that they offer excellent resistance to salt and bioactive agents, act as a pre-treatment prior to reverse osmosis by retaining solids and microorganisms, and extend the life of downstream desalination membranes.

9.9. Groundwater and surface water treatment

Groundwater is characterized by the presence of numerous contaminants such as iron, manganese, heavy metals and organic matter. Inexpensive ceramic membranes are an ideal technology for improving groundwater quality, as they remove suspended solids and chemical contaminants, improving water properties and making it more usable [259]. Ceramic membranes are non-corrosive, enabling them to treat groundwater that may contain aggressive substances harmful to other membranes. These membranes are easy to maintain and can last a long time [260]. Surface waters, such as rivers and lakes, can contain a variety of contaminants such as organic matter, agricultural pollutants and suspended solids. Ceramic membranes are an effective tool for treating these waters, thanks to their ability to precisely filter out contaminants, helping to preserve the health of the environment [261]. Ceramic membranes can effectively remove suspended substances and help reuse treated water for a variety of purposes, such as irrigation or industrial uses [262].

The advantages of using ceramic membranes in groundwater and surface water treatment are that they effectively remove particles, sediments, and pathogens, they can be used without intensive chemical pre-treatment, and they ensure good quality treated water with reduced maintenance.

9.10. Separation of bacteria and viruses from contaminated water

Ceramic membranes are used to separate biological contaminants such as bacteria and viruses from contaminated water, thanks to their fine pores, which prevent the passage of microorganisms [263]. Their ability to effectively reduce the level of bacterial and viral contamination makes them an essential component of water treatment systems in regions suffering from biological contamination [264]. These membranes help to improve the hygienic quality of water and reduce the risk of waterborne diseases such as cholera and typhoid [265].

The advantages of using ceramic membranes to separate bacteria and viruses are that their fine porosity ensures almost total retention of bacteria and viruses, they provide a lasting physical barrier against microbiological contaminants, and they do not release chemicals into the treated water.

9.11. Treatment of other wastewater

Treating wastewater from other industrial activities is a major challenge, as these waters vary in chemical and physical composition. Water from industries such as chemicals, textiles, pharmaceuticals and other plants can contain a wide range of contaminants such as organic matter, oils, fats, lipids, toxic compounds and chemicals [266]. The use of ceramic membranes is an effective and sustainable way of treating these waters. Contaminants present in wastewater from other industries vary according to the type of industry. These include oils and fats, which are found in large quantities in industries such as food and beverage, detergents and chemicals. These substances are generally difficult to treat using conventional methods such as filtration or chemical treatment.

Organic substances include biodegradable organic compounds such as fatty acids, sugar and organic matter resulting from chemical processes [267]. Toxic substances such as heavy metals (lead, zinc, cadmium) and chemicals such as industrial solvents and pesticides, and various pollutants such as dyes and chemicals contaminated by the textile or pharmaceutical industries. The advantage of ceramic membranes is their ability to effectively separate a wide range of contaminants via a filtration mechanism. This ability is based on the micropore structure of the membranes, which enables them to selectively trap contaminants. Ceramic membranes can be used in many industrial wastewater treatment processes. Filtration using ceramic membranes takes place through a filter containing micropores that trap suspended solids, fats and oils. Ce processus est très efficace pour éliminer les matières en suspension et les contaminants qui sont plus grands que la taille des pores. Thanks to their porous structure, ceramic membranes can effectively separate oils and greases from water. Oils are absorbed into the pores or trapped on the ceramic surface, enabling the filters to remove these substances from the water. Some ceramic membranes have chemical properties that enable them to remove toxic organic substances through chemical reactions between the membrane surface and the contaminants. These reactions include adsorption or catalysis of chemical reactions that lead to the neutralization of harmful substances. Ceramic membranes can also remove heavy metals from wastewater using physical processes such as adsorption, where the ceramic surface reacts with heavy metals such as lead or zinc, preventing them from passing through the membrane and reducing their concentration in the treated water. Inexpensive ceramic membranes are widely used in wastewater treatment in various industries. Ceramic membranes can withstand harsh conditions such as high temperatures, pH changes and water pressure. This feature makes them ideal for industries that may contain materials that are difficult to degrade. Ceramic membranes minimize the costs associated with conventional treatment systems such as chemical or biological treatment. Ceramic membranes are highly effective at separating fine particles such as oils, fats and solids. Ceramic membranes are usually combined with other technologies to optimize treatment efficiency. Sometimes, auxiliary chemicals such as agglomerates or solvents are used to facilitate contaminant removal, particularly in the case of organic or toxic substances. In some applications, contaminated water may require biological pre-treatment or be incorporated into ceramic membranes. Bacteria or other microorganisms are used to break down organic matter before it is used in ceramic membranes. Water from the pharmaceutical industry contains complex chemicals that can be toxic. Ceramic membranes can effectively treat this water, eliminating both toxic and pharmaceutical substances. Water from the textile industry contains synthetic colors and dyes that are difficult to degrade, and ceramic membranes can effectively filter and purify it. Ceramic membranes can filter and purify them efficiently. Ceramic membranes easily remove these compounds. Although ceramic membranes are effective in treating industrial wastewater, certain challenges must be overcome. Clogging can occur due to the accumulation of contaminants on the membrane surface or in the pores, leading to a reduction in filtration efficiency. This calls for regular maintenance and the development of effective cleaning techniques. Industries need membranes specifically designed to withstand the type of contaminants they produce [268]. It is therefore important for the future to develop new membranes capable of treating multiple contaminants. As a result, low-cost ceramic membranes are an effective and sustainable option for industrial wastewater treatment. Ceramic membranes are an important option for treating wastewater from other industrial activities. They can remove solids, oils, greases and other organic contaminants. Membrane efficiency depends on the type of contaminants contained in the water, with applications varying according to the composition of the contaminated water.

The advantages of using ceramic membranes in the treatment of various types of wastewater are that they can be adapted to a wide range of industrial effluents, they remain functional even in the presence of aggressive or complex substances, and they represent a cost-effective solution for decentralized wastewater treatment.

9.12. Membrane fouling and anti-fouling performance

The decrease in permeate flux as a function of time for the sintered membrane under a given pressure can be attributed to clogging of the ceramic membrane. The presence of colloidal particles or microorganisms on the filtration surface is the root cause of this phenomenon. The values of the estimated parameters, such as the regression coefficient (R^2), slope (k), and initial permeate flux (J_n), are indicated for each of the four models studied (the complete pore blocking model (Eq. (12)), the standard pore blocking model (Eq. (13)), the intermediate pore blocking model (Eq. (14)), and the cake filtration model (Eq. (15)). The model with the highest correlation coefficient (R^2) indicates that it accurately describes the fouling mechanism that occurs during filtration. Belgada et al. found that the cake filtration model best describes flux decline based on the R^2 values [43]. Manni et al. found that, based on the results, the cake filtration model accurately reproduced the decrease in flux [44]. This indicates that the majority of suspended particles are larger than the membrane pore size. Purnima et al. determined that cake filtration was the most accurate model for the experimental permeate flux, based on the regression coefficient ($R^2 = 0.99$) and the initial permeate flux values [56]. Vinoth Kumar et al. found through the analysis of the fouling mechanisms using different pore blocking models that the cake filtration model represents the best model for the experimental data [99]. Suresh et al. presumed that the cake filtration model accurately depicts the fouling mechanism for the ceramic support, while the complete pore blocking model accurately depicts the TiO_2 membrane [197]. Hatimi et al. clearly demonstrated that cake formation was the most appropriate model for describing the experimental filtration flux, with correlation coefficients of 0.98 and 0.99 for TW and DW, respectively [84]. Beqqour et al. found that the flux decline in S1 could be simulated by the intermediate pore blocking model [161]. In the case of S2, both the standard pore blocking model and the intermediate pore blocking model may be suitable for describing the flux decline. El Machtani Idrissi et al. found that E1 could be explained by the intermediate pore blocking model, which suggests that E1 contains particles of a similar size to the pores in the membrane. For E2, it is simulated by the complete pore blocking model. This suggests that the particles are blocking pore entry due to their larger size compared to the membrane pores [206] .

The antifouling capacity of membranes is an essential property for evaluating performance. After the filtration process, the membrane is carefully cleaned with a suitable solution (such as alkaline, acid, or demineralized water) to remove deposits and restore its initial permeability. The choice of cleaning solution depends on both the nature of the pollutants present and the nature of the membrane [147]. The antifouling characteristics of the membrane were measured (Table 5) including FRR (flux recovery rate), RFR (reversible flux decline rate), TFR (total flux decline rate) and IFR (irreversible flux decline rate), using Eqs. (16)–(19).

10. Membrane separation mechanisms

The ceramic membrane treatment process is one of the most advanced methods of water treatment. It consists of several main stages designed to remove contaminants of different sizes and characteristics. These stages differ in their techniques and methods, depending on the chemical and physical properties of the treated water and the membranes used (Fig.7).

The initial stage in the ceramic membrane water treatment process is the preparation stage, which is essential to guarantee the effectiveness of ceramic membranes. During this stage, contaminated water is pre-treated by techniques such as mechanical or chemical filtration to

Table 5
Membrane recovery and antifouling ability.

Membrane material	Cleaning solution	Membrane type	polluants	FRR,%	TFR,%	RFR,%	IFR,%	Reference
Natural phosphate	–	MF	Seawater	74.25	70.84	46.84	23.99	[43]
Phengite clay	Demineralized water	MF	Wastewater from clothes washing	84.90	69.70	54.60	15.10	[117]
Phengite clay/ corn starch	Demineralized water	MF	RSW1	80.00	30.00	10.00	20.00	[147]
	Demineralized water		RSW2	80.00	25.00	5.00	20.00	
Attapulgite (ATP) nanofibers / ferroferric oxide (Fe_3O_4) nanoparticles	Hot water	MF	Oil-in-water	86.50	–	–	–	[269]

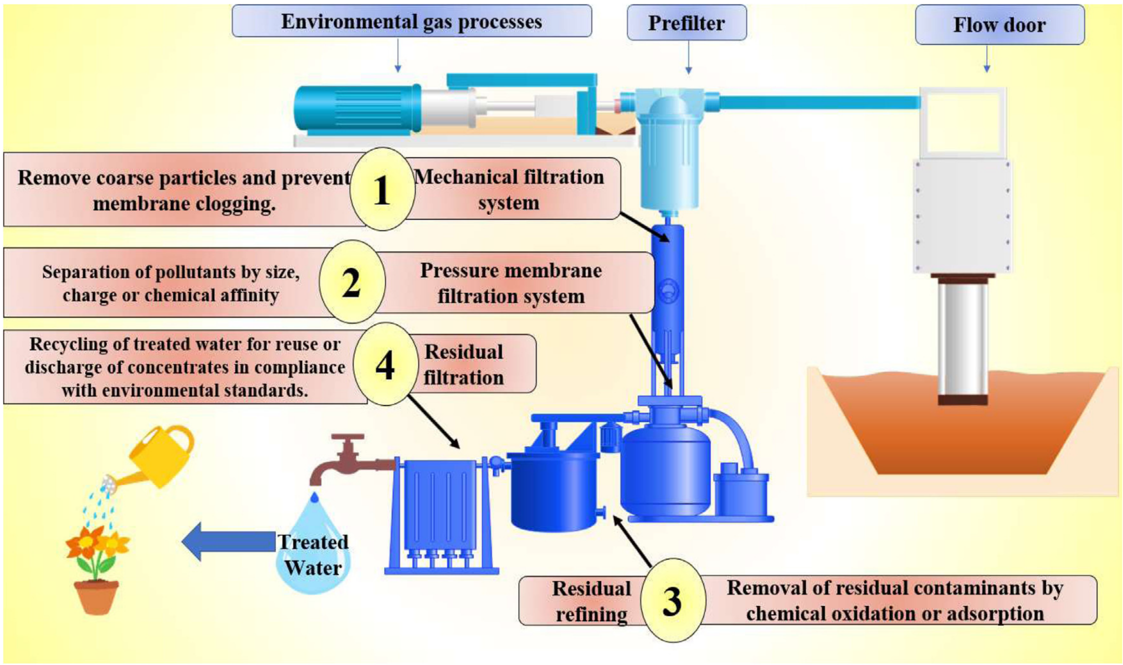

Fig.7. Separation mechanisms using filtration on ceramic membranes.

remove coarse particles and suspended solids [270]. These large particles can clog membrane pores, reducing the system's efficiency in water treatment. Mechanical filtration removes large particles such as solid debris and insoluble sediments from the water. This stage uses large-pore filters (such as sand filters or mesh filters) that trap microscopic or larger particles such as sand, debris and certain organic matter that may affect the subsequent separation process. Mechanical filtration is the first step required to ensure that ceramic membranes are not clogged when in use. In some cases, water may contain solvents or chemical contaminants that can affect membrane performance. Consequently, chemical filtration techniques such as treatment with chlorine oxide, ozone or other auxiliary chemicals are used to remove organic matter or toxic compounds that may damage the membrane [271]. In this way, the water is prepared to be free of contaminants that may react with the ceramic material and reduce its efficiency. This step is crucial to ensure that the operating efficiency of ceramic membranes is maintained throughout their service life, and to avoid blockages and other defects.

The second stage is the most important part of the treatment process using ceramic membranes, where the membranes are used to separate contaminants from the water thanks to a certain pressure that forces the water through the ceramic membranes [272]. At this stage, the contaminants to be separated are determined according to their size, charge and chemical nature. Separation in ceramic membranes is mainly based on particle size. Ceramic membranes are designed with different types of pore to separate particles and salts of different sizes. Microfiltration membranes, which can separate particles between 0.1 and 10 μm in size, such as bacteria and microorganisms. Ultrafiltration, which can separate particles larger than 0.01 μm , such as proteins, dissolved organic matter and certain microparticles. Reverse osmosis, based on membranes with very fine pores, capable of separating very small particles such as salts, heavy metals and dissolved organic compounds. In some cases, ceramic membranes rely on the electrical charge of molecules to filter out contaminants. For example, ceramic membranes can have surface charges that affect the movement of molecules in solution [273]. Similarly charged molecules can be trapped on the membrane surface, preventing them from passing through the pores. This type of separation is used to remove contaminating ions or certain compounds with an electrical charge. The separation process at this stage may also be the result of chemical or biological reactions occurring between the membrane and the water. For example, membranes can undergo oxidation or reduction reactions when in contact with chemical compounds or contaminants, reducing the chemical concentrations of these contaminants before they can pass through the pores [274].

Once the water has passed through the ceramic membranes in the second stage, residual contaminants may remain in the water, which have not been fully separated. At this 3rd stage, further treatment using other technologies is required to guarantee the purity of the water. Chemical oxidation is used to remove organic matter and contaminants that may resist membrane separation. An oxide such as ozone or chlorine is used at this stage to break down residual organic compounds or toxins, making them more amenable to separation using ceramic membranes or other methods [275]. Oxidation is an effective process for removing toxic organic compounds or contaminants that cannot be separated using membranes alone. Activated carbon filtration is an important secondary treatment method in water treatment. At this stage, carbon filters are used to remove contaminants such as soluble organics, colors, and odors. Activated carbon is a highly porous material, and contaminants are adsorbed to its surface, helping to improve water quality after treatment.

The 4th stage consists of treating the residues from the ceramic membrane separation process. Sometimes, the filtered components are reused in the filtration process or other applications, such as treated water for industrial or agricultural purposes [276]. In other cases, contaminants are safely disposed of in accordance with environmental standards. Recycling can include the use of treated water in other industries or in agriculture. This minimizes water losses and ensures environmental sustainability. If residual contaminants or solids cannot be reused, they are disposed of according to environmental standards and local health legislation.

10.1. Advanced research on ceramic nanomembranes

Recent research shows significant progress in the field of ceramic membranes, notably through the introduction of functional nanomaterials, hybrid structures, or the integration of eco-responsible cleaning processes and predictive models assisted by artificial intelligence (Table 6). These approaches aim not only to improve filtration performance, but also to meet sustainability and circular economy imperatives. Baig et al. applied a thin layer of ZnO by RF sputtering to alumina membranes for the treatment of oil effluents. This coating makes the surface superhydrophilic in air and super-oleophobic under water, with a separation efficiency of 99.66%. UV irradiation triggers photo-catalytic degradation of organic pollutants, enabling flux recovery of 88% [33]. Bartoletti et al. deposited a nanostructured coating based on perovskites and fluorites on ceramic membranes for hydrogen separation. Flux was more than doubled, without structural degradation, thanks to improved dispersion of platinum catalyst particles [277]. Duan et al. and Duan et al. used CuO and MnO_2 coatings combined with micro-nano bubbles, alone or with hydrogen peroxide, to trigger the formation of reactive oxidizing species. These catalytic membranes enable advanced degradation of organic pollutants with over 99% decolorization for methylene blue [278,279]. Kim et al. highlighted the interest of 2D materials (graphene oxide, MXene, MoS_2, h-BN) to improve the durability, chemical resistance, and permeability of membranes in harsh industrial environments such as the semiconductor industry [280]. Li et al. modified a ceramic disk membrane with nano-TiO_2 to improve dynamic filtration. Separation efficiency reached 99.9%, with flow maintenance and reduced fouling [281]. W. Liu et al. have demonstrated that backwash cleaning with ozone-micro-nano bubbles significantly reduces resistance to irreversible fouling and improves membrane life [282]. Y. Liu et al. have designed a MoS_2/MoO_3 heterostructure membrane, significantly improving hydrophilicity without compromising permeability. This modification enables high nanofiltration efficiency and excellent mechanical stability, with a low-pollution integrated thermal approach [283]. Zhong et al. have developed a TaC membrane with integrated nano-Pd for the electrochemical reduction of CO_2 to formate, illustrating the potential of membranes in the recovery of greenhouse gases, while combining advanced manufacturing techniques (pressureless sintering, controlled hydrophobization) [284]. Solaiman et al. list various nanocomposite membranes incorporating TiO_2, Al_2O_3, and zirconia, showing dye retention efficiencies of 95%–100%. These materials demonstrate the viability of selective recovery and recycling of high-value-added pollutants (textile dyes), with a view to circularity [285]. Mo et al. demonstrate the effectiveness of ozone micro-nano bubbles for in-situ cleaning of ceramic membranes. This method enables 100% flux restoration without the use of aggressive chemicals, while limiting the environmental impact of treatment [286]. Wang et al. couple these bubbles to catalytic ceramic membranes Co_3O_4/Al_2O_3 for the treatment of reverse osmosis concentrates, enabling enhanced pollutant degradation with a 2.5-fold reduction in operational cost compared to conventional ozonation. The approach also improves membrane durability by reducing clogging [287]. Shim et al. develop an integrated micro/nano bubble assisted flotation system combined with ceramic filtration, for the treatment of oil sands wastewater. The absence of chemical additives and the effectiveness on oily phases demonstrate the potential of circular processes without polluting reagents [288]. Usman et al. integrate machine learning algorithms to predict the performance of polymer/nanoceramic membranes designed to treat oily effluents from the palm oil industry. These tools improve real-time management, reduce costly physical testing, and are part of a systemic and sustainable efficiency approach [30].

11. Cost analysis of ceramic membranes

Ceramic membranes are one of the advanced systems used in wastewater treatment. They are characterized by their ability to improve water quality through efficient filtration and purification. The manufacturing process for these membranes requires several steps that depend on raw materials and advanced manufacturing techniques, which influence the economic costs of these systems. In this context, costs can be divided into two main parts: manufacturing costs and application costs (Fig.8).

Ceramic membranes require materials such as clay, silica, aluminum oxide and other mineral materials, which are added to the ceramic paste. The manufacturing process involves preparing the raw material, shaping it into films using techniques such as extrusion or molding, then drying and fritting in high-temperature furnaces at over 1000 °C [289]. These processes are costly, especially in the first phase, as they require specialized equipment such as industrial furnaces and manufacturing tools.

Some recent research has focused on the manufacture of ceramic membranes from local natural materials, such as clay or phosphate, to reduce the high production costs associated with conventional industrial ceramic membranes, notably those based on α-alumina or stainless steel, with costs ranging from 500 to 3000 $\$/m^2$ [99]. Although commercial polymer membranes could be around 50 to 200 $\$/m^2$, studies have shown that ceramic membranes derived from local raw materials can achieve competitive costs [56]. For example, some tubular membranes made from inexpensive clay are estimated to cost around 0.5 $ per membrane, equivalent to 69 $\$/m^2$, bringing them close to polymer membranes in terms of cost [163]. Other studies mention a manufacturing cost of around 61 $\$/m^2$, and some monolithic mullite prototypes have even reached lower estimates, around 13.86–15.77 $\$/m^2$ [203,204]. In our previous study, we manufactured a flat membrane from inexpensive natural clay, with an estimated manufacturing cost of approximately 125 $\$/m^2$ [147].These results suggest that, despite the generally expensive manufacturing processes for ceramic membranes, it is possible, in certain specific cases and using simplified processes, to develop more economical ceramic membranes.

After the initial manufacturing process, the membrane may require additional modifications such as deposition of an active membrane layer to enhance its efficiency and flexibility, which increases the overall cost. The membrane may also require rigorous quality testing to ensure its effectiveness, adding to the cost. It's important to factor in the cost of

Table 6
Ceramic nanomembranes applications.

Type of modification	Main function	Key performance	Sustainable circular aspect	Reference
ML modeling of nanocomposite membranes	POME effluent treatment optimization	NSE >99% for oil discharge	Reduction of experimental trials, continuous assessment, EPA, and SDG impact	[30]
ZnO on Al_2O_3	Photocatalysis, self-cleaning	99.66% separation; 88% flow recovery	UV cleaning and chemical reduction	[33]
CuO on Al_2O_3	ROS via MNB collapse	88.9% MB abatement	No added reagent process	[279]
2D materials (GO, MXene, etc.)	Ceramic membrane reinforcement	Improved chemical stability	Disposable polymer reduction	[280]
TiO_2 on the membrane disk	Hydrophilicity, oil/water separation	99.9% separation	Dynamic, anti-fouling filtration	[281]
O_3−MNB for cleaning	Fouling reduction	RFi 4.8% (vs 100%)	Reduced chemical cleaning	[282]
MoS_2/MoO_3 heterostructure (thermal oxidation)	Hydrophilic enhancement for nanofiltration	97.4% retention of Xylenol Orange, 32.8 L/(h·m^2·bar)	Simple thermal process, no channel blockage, longer service life	[283]
Electrode membrane TaC + Pd + hydrophobic layer	Electrochemical reduction of CO_2 to formate	FE formate 54%, 25.4 mA cm^{-2}	CO_2 upgrading, long-term stability, and advanced integrated materials	[284]
Nanocomposite membranes (TiO_2, Al_2O_3, ZrO_2)	Textile dye filtration	Up to 100% azo colorant retention	Recycling of resources, high chemical resistance, and potential for reuse	[285]
Micro-nano bubble ozone cleaning	Ecological chemical cleaning	100% flow recovery	Reduced use of chemicals, reduced environmental impact	[286]
Coupling MNBs + catalytic membrane Co_3O_4/Al_2O_3	RO industrial concentrate treatment	Operating cost reduction x2.5, high catalytic stability	Reduced clogging, low catalyst leaching, economically sustainable process	[287]
IGF-MNBs integration with ceramic filtration	Additive-free oily water treatment	11% flotation and 19% SS removal improvement	No chemical additives, optimization of a sustainable integrated process	[288]

maintaining the membrane over its lifetime. It may be necessary to periodically clean membranes of bioaccumulations and deposits, as well as to periodically replace damaged or worn membranes. In addition, ceramic membranes often require energy to operate efficiently, particularly in continuous filtration systems. Energy consumption is a significant cost in the process, which can increase the operational cost of systems in the long term. The system requires maintenance of the ceramic membranes by cleaning them and eliminating bio-accumulations. Although the manufacture of ceramic membranes has evolved, a great deal of research is underway to optimize their performance and reduce production costs. To optimize treatment efficiency, ceramic membranes may need to form part of integrated treatment systems. They can be combined with technologies such as biological or solar water treatment to achieve maximum efficiency. However, this requires the development of integrated, flexible systems. A recent trend is the development of environmentally-friendly ceramic membranes. This can be achieved by using recyclable raw materials and optimizing the energy efficiency of treatment systems. Consequently, the manufacturing and application costs of ceramic membranes in wastewater treatment are high compared to other solutions such as polymer membranes, but the advantages of these membranes in terms of durability, endurance and efficient filtration solutions make them a preferred option in certain applications. On the other hand, ongoing research into manufacturing techniques and the integration of ceramic membranes with other technologies can help reduce production and application costs and increase the viability of large-scale industrial development.

12. Conclusion

Low-cost ceramic membranes have shown great potential for improving environmental and industrial performance in water and wastewater treatment. These membranes are capable of effectively removing contaminants, both organic and inorganic, including heavy metals, bacteria and viruses. The growing need for water treatment solutions in many parts of the world, particularly in developing countries, has led to great interest in this technology. Low cost is an important factor in making these membranes an attractive option for many industrial applications. Several methods of manufacturing ceramic membranes have been highlighted, such as extrusion, slip casting, which are easy to implement and inexpensive compared to other traditional methods such as freeze casting. These techniques offer great flexibility in the preparation of membranes for different industrial applications, as well as significant effects on the physical properties of membranes, such as porosity, permeability and hardness. The characterization of ceramic membranes has been studied in depth using techniques such as scanning electron microscopy, X-ray analysis and measurements of water absorption and bulk density. These properties are essential for determining the functional performance of membranes in filtration and contaminant separation processes. The results showed that ceramic membranes have high mechanical strength and can withstand harsh environmental conditions, making them suitable for use in a variety of industries. The resistance of membranes to various chemical conditions likely to be encountered during their use was also investigated, contributing to membrane service life. Despite the great advantages of ceramic membranes, they face many challenges, the most important of which is the problem of membrane clogging resulting from the accumulation of substances on their surface, such as proteins, oil and organic matter. This fouling degrades membrane performance and reduces its efficiency in filtration processes. Therefore, research is being carried out into techniques to minimize fouling, such as the use of antifouling materials and the modification of membrane properties to improve resistance to surface build-up. The industrial applications of ceramic membranes are many and varied, rang-

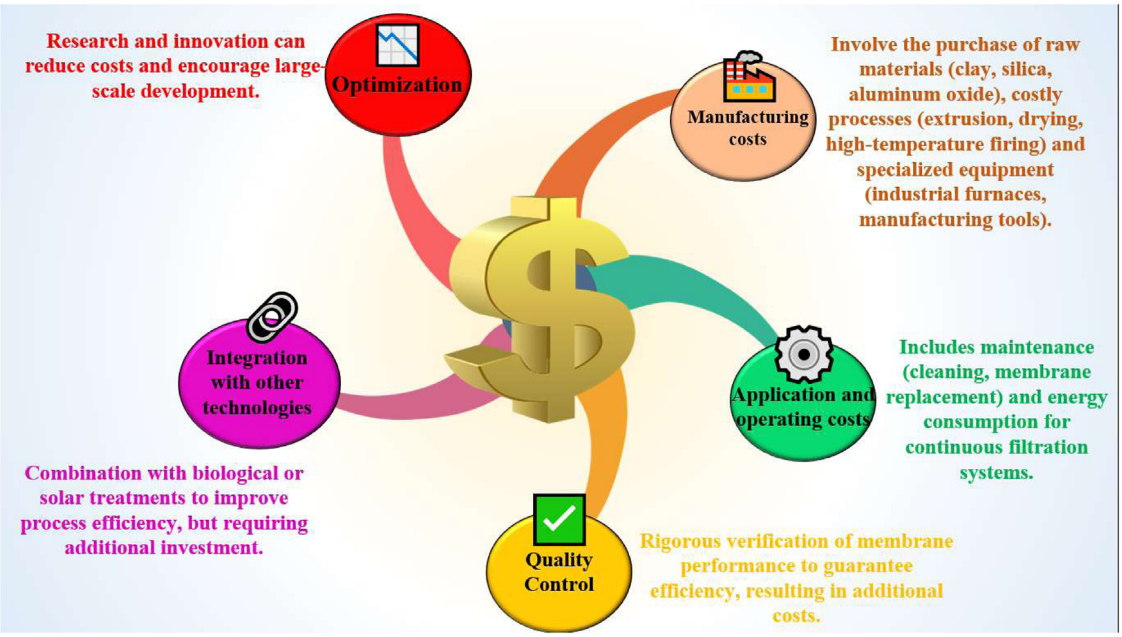

Fig.8. Cost estimation nodes for the application of ceramic membranes in aqueous effluent treatment.

ing from wastewater treatment in industries such as textiles, tanneries and paper mills, to seawater and groundwater treatment. With growing interest in the conservation of water resources, ceramic membranes are emerging as an effective tool for purifying water and reducing treatment costs. Practical studies have shown that these membranes give promising results in removing contaminants and improving the quality of treated water. Economic analysis of the application of ceramic membranes is an essential element in assessing the feasibility of their use in water treatment. Oxide-based inorganic materials are generally more expensive than polymers. However, by using abundant natural materials, the cost can be considerably reduced. In addition to this economic advantage, membranes made from these materials have interesting properties such as good thermal stability, excellent chemical resistance, and high mechanical strength. Despite these economic advantages, maintenance costs and ongoing performance need to be taken into account to guarantee the effectiveness of the long-term benefits. Despite significant progress in the development of low-cost ceramic membranes, a number of challenges remain, such as improving membrane performance, reducing energy consumption during manufacture and developing new antifouling technologies. There is also a need for further research into the durability and recyclability of the raw materials used. Future research is focused on improving the performance of ceramic membranes through new technologies such as the use of nanomaterials to enhance filtration capacity and minimize fouling. New ways to improve the environmental sustainability of ceramic membranes through the use of local and renewable raw materials, as well as by focusing on more efficient manufacturing techniques. Low-cost ceramic membranes are a promising option in water and wastewater treatment, thanks to their multiple advantages in terms of cost and performance. Despite the challenges it faces, this technology still occupies an important place in many industrial and environmental applications. Continued research into improving membrane technologies and extending their applications will make a significant contribution to meeting global environmental challenges and sustainability goals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Salek Lagdali: Writing – original draft. **Mohamed El-Habacha:** Writing – review & editing. **Mohammed Benjelloun:** Writing – review & editing. **Mohamed Lasfar:** Writing – review & editing. **Guellaa Mahmoudy:** Writing – review & editing. **Abdelkader Dabagh:** Writing – review & editing. **Youssef Miyah:** Writing – review & editing. **Soulaiman Iaich:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Mohamed Zerbet:** Writing – review & editing.

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