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| RESEARCH ARTICLE

Application of Ceramic Membranes for the Removal of Heavy Metals and Dyes: Efficiency and Performance Review

Chukwunonso N. Onyenanu[1] ✉ **and Joseph T. Nwabanne**[2]
[12]*Department of Chemical Engineering, Nnamdi Azikiwe University, Awka, Nigeria*
Corresponding Author: Chukwunonso N. Onyenanu, **E-mail**: cn.onyenanu@unizik.edu.ng

| ABSTRACT
This study reviews the effectiveness of ceramic membranes in eliminating heavy metals and dyes from wastewater, focusing on their performance, material properties, and areas of application. Ceramic membranes are perfect for demanding industrial environments because of their strong mechanical strength, stability at high temperatures, and exceptional chemical resistance, especially when using ultrafiltration and nanofiltration technologies. Several critical factors that impact removal efficiency include the size of the membrane pores, the surface charge, the hydrophilic nature, and the overall structure. The studies examined range over the past twenty years, with a marked increase in publications anticipated between 2022 and 2025, indicating a heightened interest in sustainable and cost-effective membrane technologies. The review highlights the increasing use of low-cost, waste-derived materials such as rice husk, fly ash, sugarcane bagasse, and red mud in membrane production, contributing to cost reduction and environmental benefits. Hybrid systems that combine ceramic membranes with techniques like electrocoagulation, advanced oxidation, or distillation have achieved pollutant rejection rates frequently surpassing 95–99%. Nevertheless, the high costs associated with production and the limited practical application at full scale pose significant challenges. This review brings together technical insights, contrasts different membrane types, and evaluates trends and gaps, providing valuable perspectives for researchers and industry players looking to enhance water treatment technologies with effective ceramic membrane solutions.

| KEYWORDS

Ceramic membranes, Heavy metal removal, Dye separation, Wastewater treatment, Water purification technologies.

| ARTICLE INFORMATION

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1. Introduction

To address the growing water scarcity issue, efficient advanced treatment technologies are essential for effective water and wastewater purification, leading to the rising trend of synergistic coupling systems (X. Chen et al., 2023; Mansas et al., 2020a; Zhao et al., 2018). Over the past few decades, the use of membranes in water treatment has grown significantly, primarily due to advancements in materials and processing techniques (De Angelis & de Cortalezzi, 2013). Membranes have become a key element in wastewater management, particularly in membrane bioreactors (MBRs) (De Angelis & de Cortalezzi, 2013; Meng et al., 2010; Pollice et al., 2005). In fact, the global market for ultrafiltration (UF) membranes is projected to rise from 0.95 billion USD in 2017 to 2.14 billion USD by 2023 (Al Aani et al., 2020; Asif & Zhang, 2021). Pressure-driven membranes are utilized in various applications such as water treatment, wastewater recycling, and desalination (Ang et al., 2015; W. Gao et al., 2011; Teychene et al., 2018). The benefits of this technology include a reduced spatial requirement and enhanced separation of microorganisms; however, there is a need for membranes that can resist strong chlorine, a condition that many commercially available membrane materials fail to meet (De Angelis & de Cortalezzi, 2013). When compared to traditional filtration methods, membrane-based separation techniques are both compact and durable, offering high-quality treated effluent (Asif & Zhang, 2021). Membranes can effectively eliminate or reject a variety of contaminants, including suspended solids and pathogens, through mechanisms like size exclusion, adsorption, and electrostatic repulsion (Asif & Zhang, 2021; W. Gao et al., 2011; Taheran et al., 2016).

Ceramic membranes have been documented as exhibiting significant thermal stability and resistance to various chemicals, accompanied by an extended operational lifespan, thereby rendering them particularly suitable for applications involving industrial wastewater treatment and oil/water separation (C. Li et al., 2020; Xing, 2017). Notably, their uses for mild-condition water and wastewater treatment have drawn a lot of interest recently (Hubadillah, Othman, Matsuura, et al., 2018; Jeong et al., 2017). However, because of their high initial cost, their utilisation in full-scale applications is still restricted (Asif & Zhang, 2021). The goal is to create ceramic membranes using inexpensive natural materials like kaolin and pyrophyllite (Alresheedi et al., 2019; Goswami & Pugazhenthi, 2020). Ceramic membrane-based water and wastewater treatment methods (such as membrane bioreactors) have demonstrated encouraging outcomes and have been shown to outperform polymeric membranes based on lab-scale research (Asif et al., 2020a, 2020b, 2021). To improve pollutant removal and membrane fouling mitigation, a number of physicochemical processes, including coagulation and advanced oxidation processes (AOPs), have been coupled with ceramic membrane bioreactors (CMBR) and standalone ceramic membranes (Fang et al., 2011; Goei & Lim, 2014; Konieczny et al., 2006; Wei et al., 2016). However, a comprehensive techno-economic analysis is imperative to inform the selection of integrated physicochemical methodologies for full-scale implementation (Asif & Zhang, 2021). In recent endeavors aimed at augmenting antifouling characteristics, pollutant elimination efficacy, and disinfection capabilities, ceramic membranes have undergone coatings or modifications with diverse (nano) materials such as TiO_2, Ag, and MnO_2 (Guo et al., 2015; He et al., 2019; Horovitz et al., 2016; Ishak et al., 2017; M. Lee et al., 2015; Mansas et al., 2020b). The resulting catalytic ceramic membranes present a compelling proposition; however, their performance evaluations are predominantly conducted through short-term experimental frameworks (Asif & Zhang, 2021). Furthermore, it is essential to validate the stability and reusability of these membranes after treatment with real-world water matrices.

This review examines how effective ceramic membranes are at eliminating heavy metals and dyes from polluted water, considering important factors like pore size, surface charge, hydrophilicity, and the configuration of the membranes (John, Ezechukwu, et al., 2025; Uzochukwu, Okey-Onyesolu, et al., 2025; Godspower et al., 2024; Ekwueme et al., 2023; Ajali, Umenwa, et al., 2023). Numerous outstanding reviews on ceramic membranes have been released in recent years (Alresheedi et al., 2019; Y.-R. Chen et al., 2018; Goswami & Pugazhenthi, 2020; Hubadillah, Othman, Matsuura, et al., 2018). These reviews cover various membrane fabrication techniques and their effectiveness in treating industrial wastewater, as well as the use of nanocomposite membranes to reduce fouling (C. Onyenanu & Emembolu, 2020a; Ajali & Onyenanu, 2023; Ajali, Victor, et al., 2023; Uzochukwu, Onu, et al., 2025; C. Onyenanu & Nnanyelum, 2020; L. Emembolu et al., 2020; Ogbodo et al., 2023). However, there has not been a thorough assessment of the current state of full-scale applications and market potential for ceramic membranes (Uzochukwu, Ezechukwu, et al., 2025; John, Onu, et al., 2025; Uzochukwu, Kanwulia, et al., 2025). Thus, this review seeks to examine the performance and effectiveness of ceramic membranes (particularly ultrafiltration and microfiltration) to assess their present situation in water and municipal wastewater treatment (C. Onyenanu & Emembolu, 2020b; L. N. Emembolu et al., 2021; C. N. Onyenanu et al., 2023).

2. Literature Review

The review employed a systematic literature analysis to evaluate the effectiveness of ceramic membranes in removing heavy metals and dyes from wastewater. Researchers like Solaiman et al. (2024), Jiang et al. (2022), and Chen et al. (2019) performed laboratory-scale investigations evaluating membrane rejection capacity, flux stability, and fouling characteristics through various setups, including ultrafiltration, microfiltration, and nanofiltration. Research conducted by El Maguana et al. (2024), Hubadillah et al. (2018), and Aziz et al. (2019) examined the application of affordable and sustainable materials such as rice husk, sugarcane bagasse ash, and aluminum dross for membrane production. Additionally, studies by Atallah et al. (2024) and Rakcho et al. (2024) looked into hybrid systems that combine ceramic membranes with electrocoagulation and adsorption techniques, frequently accompanied by modeling or analyses of surface charge. The selection and inclusion of studies adhered to the PRISMA framework, leading to the final choice of 30 articles with validated experimental findings. The focus was on pollutant-specific performance, sustainability of materials, and scalability of applications, which ensured a thorough comprehension of the technical efficiency and future prospects of ceramic membrane technologies in wastewater treatment.

3. Methodology

This study uses a structured literature analysis to objectively evaluate the effectiveness and efficiency of ceramic membranes in extracting heavy metals and dyes from wastewater. The review focuses on filtering performance indicators, pollutant rejection rates, membrane material parameters, and operational factors that influence treatment efficiency. Specific emphasis was paid to microfiltration and ultrafiltration ceramic membranes, with comparisons made across synthesis pathways, application domains, and membrane topologies.

3.1 Data Collection and Selection

The databases Scopus and ScienceDirect were chosen because they widely index influential, peer-reviewed journals in the fields of environmental science, materials engineering, and water treatment. A Boolean search approach was utilized to ensure a thorough inclusion of pertinent literature:

- ("ceramic membrane" OR "inorganic membrane")
- AND ("heavy metal removal" OR "dye removal" OR "wastewater treatment")
- AND ("filtration efficiency" OR "performance evaluation" OR "rejection rate" OR "flux")

The search included more than 20 years of scientific progress in ceramic membrane research and use, covering articles from 2001 to 2025. Following the initial retrieval of 535 papers, inclusion criteria were applied, including relevance to membrane-based water treatment, experimental validation, and quantitative performance indicators. After full-text reviews and abstract screening, 30 studies were chosen for further examination.

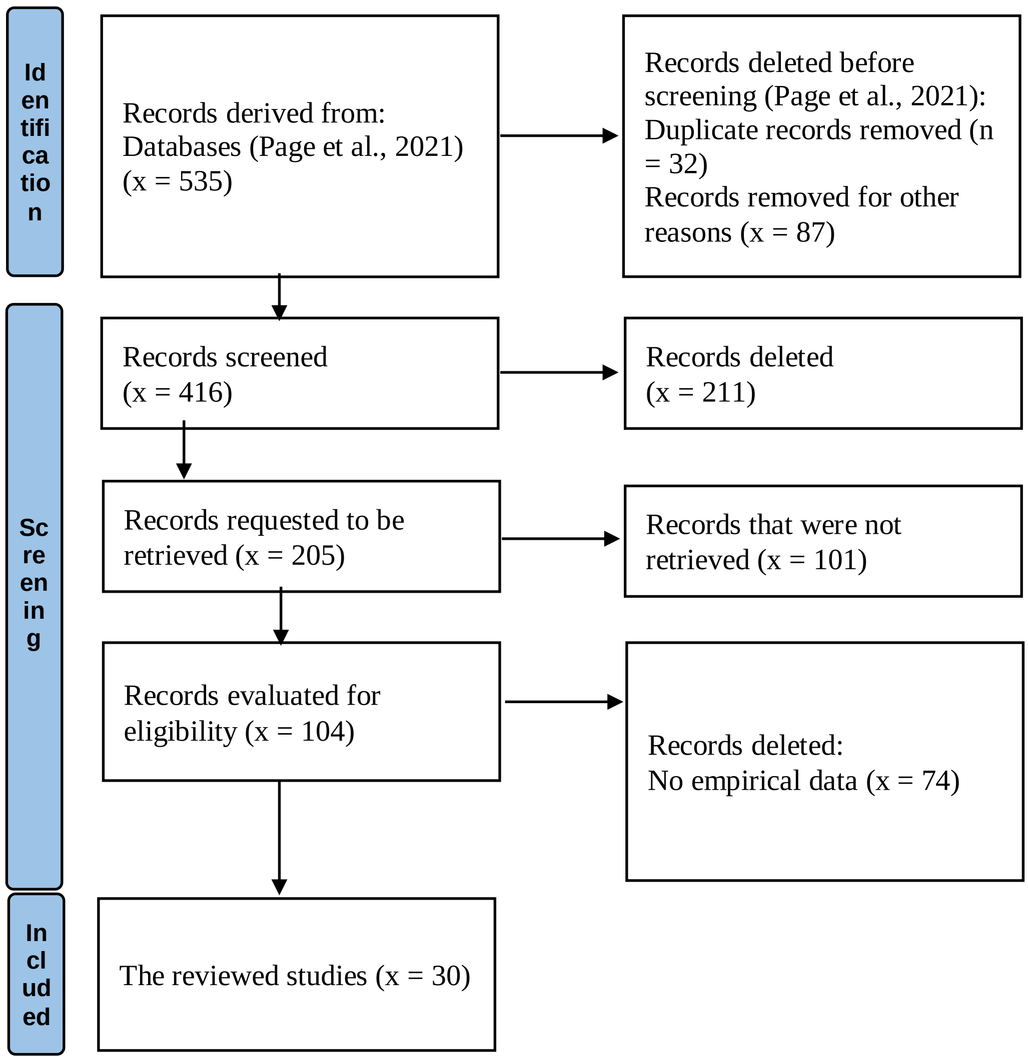

Figure 1: PRISMA Flow Chart Illustrating the Literature Selection Process (Source: Page et al., 2021)

3.2 Data Collection and Selection

As illustrated in Figure 2, there has been a significant increase in scholarly interest regarding the use of ceramic membranes for the removal of heavy metals and dyes, particularly over the past five years. This trend highlights the field's connection to global issues concerning the management of industrial wastewater and the move towards sustainable treatment technologies. Among the 30 papers analysed, 66.7% (20 studies) were published between 2022 and 2025, indicating a significant rise in research effort over this period. This growth aligns with swift advancements in the design of nanocomposite membranes, environmentally friendly fabrication techniques, and hybrid treatment methods. The escalation in research efforts not only emphasizes the importance of ceramic membrane technologies in contemporary wastewater treatment but also indicates a growing assurance in their scalability, performance, and lasting effectiveness in both municipal and industrial applications.

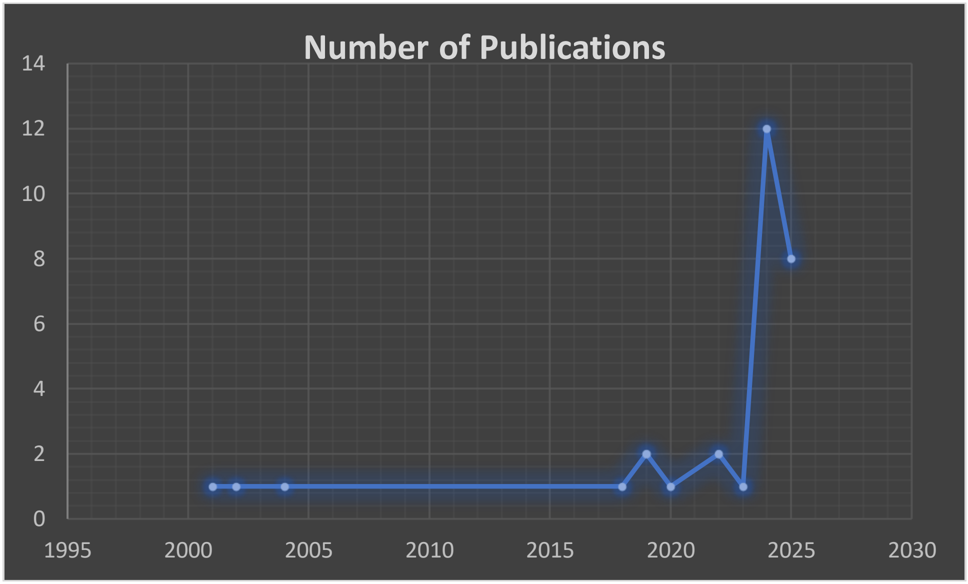

Figure 2: Graph of Journal Article by Year of Publication (Osobajo et al., 2017)

4. Reviews

Ceramic membranes have been shown to effectively remove heavy metals (e.g., Pb^{2+}, Cd^{2+}, Cr^{6+}) and dyes (e.g., methylene blue, azo dyes) in various configurations, including ultrafiltration (UF), nanofiltration (NF), and hybrid membrane systems. Furthermore, several recent studies emphasise the use of environmentally benign and low-cost precursors such as rice husk, fly ash, sugarcane bagasse, and red mud, which make the production of ceramic membranes more economically viable and sustainable. The table below (Table 1) presents an organised summary of these investigations. It provides a comparative review of the important findings, target contaminants, and membrane performance metrics from each example. This compilation provides the database for analysing technical trends, evaluating performance gaps, and forecasting the future scalability of ceramic membrane technology in wastewater treatment applications.

Table 1. Summary of Reviewed Studies on Ceramic Membranes for Heavy Metal and Dye Removal in Wastewater Treatment

S/N	Study Topic	Findings	Author(s) & Year
1	*Nanocomposite ceramic membranes as novel tools for remediation of textile dye wastewater – A review of current applications, machine learning based modeling, and future perspectives*	"The best-performing nanocomposite membranes for eliminating azo dyes from textile effluent and efficiencies achieved are reported as Clay-alumina (99%), yttria-stabilized-zirconia (99%), nano TiO_2-bentonite UF (95%), and tight TiO_2 UF (100%). Ceramic nanocomposites with TiO_2 and Al_2O_3 active layer NF (99%), Ceramic Hybrid hollow fiber LNF (99.3%). Loose nanofiltration (LNF) ceramic membranes have demonstrated outstanding targeted separation performance for the separation of dyes, making them affirm the effective recoveries and recurrent use of high-value-added constituents amongst all the membrane approaches examined."	(Solaiman et al., 2024)
2	*Research on water and waste heat recovery from flue gas using micron ceramic membranes*	"The simulation analysis showed that the increase in boiler load increased the recovery of water and waste heat, which water recovery rate increased from 21.66 kg/h to 26.62 kg/h and heat recovery power increased from 24545.11 kW to 45950.81 kW, but the efficiency decreased, which still remained above 70%. Under full-rated conditions, the FGD tower can reduce evaporation by 100 tons of water per hour when the condensate flow rate is 180 kg/s.	(Luo et al., 2023)
3	*Application of nanoporous ceramic membrane derived from Fe/S/Si/Al/O-rich mining solid waste in oil–water separation and heavy metal removal of industrial high-concentration emulsifying wastewater*	"Based on the analysis of membrane contamination behavior, the ceramic membranes prepared could restore nanoporous channels only by ultrasonic treatment. In addition, 100% removal performance of iron and copper was obtained, and 78.6% removal efficiency was achieved for Chromium and cadmium. These fascinating characteristics make the novel ceramic membrane an excellent candidate with a high oil–water separation ability."	(D. Jiang et al., 2022)
4	*Recycling of waste attapulgite to prepare ceramic membranes for efficient oil-in-water emulsion separation*	"When used for oil-in-water emulsion filtration, the permeate flux reached 236.8 $L\ m^{-2}\ h^{-2}\ bar^{-1}$ under a low transmembrane pressure of 0.2 bar, and the oil rejection exceeded 99%. Membrane cleaning with a simple ultrasonic treatment could easily achieve flux recovery."	(C. Wang et al., 2022)
5	*Ceramic nanofiltration and membrane distillation hybrid membrane processes for the purification and recycling of boric acid from simulated radioactive wastewater*	"In the nanofiltration process, the retention rates of Co^{2+} and Ag^+ ions were approximately 99.2% and 75.8%, respectively, and the permeation flux was stable at approximately $178\,L\,m^{-2}\,h^{-1}$. When a two-stage NF process was implemented, the removal of Co^{2+} ions was higher than 99.9%, and the removal of Ag^+ ions was greater than 95%. In the membrane distillation process, the boric acid was concentrated from 1 to $107\,g\,L^{-1}$. Meanwhile, the permeation flux was maintained above $20\,L\,m^{-2}\,h^{-1}$, and the retention rate of boric acid was maintained at a high level (>99.9%) throughout the entire enrichment process. The hybrid membrane processes are suitable	(X. Chen et al., 2019)

		candidates for the purification and recycling of boric acid from radioactive wastewater.”	
6	*Fabrication of low-cost, green silica-based ceramic hollow fibre membrane prepared from waste rice husk for water filtration application*	“As a result, high PWF with value ~ 300 L/m^2 h and stable at 20 min was obtained. Due to the excellent pure water flux, the prepared ceramic membrane from waste rice husk holds promise for water treatment applications.”	(Hubadillah, Othman, Ismail, et al., 2018)
7	*Pretreated aluminium dross waste as a source of inexpensive alumina-spinel composite ceramic hollow fibre membrane for pretreatment of oily saline produced water*	“The hollow fibre sintered at 1275 °C offers 92.41% rejection percentage of oil, the highest after 50 min of stable flux. Furthermore, turbidity was found to decrease from 378 NTU to 28.5 and 22.5 NTU for hollow fibres sintered at 1250 and 1275 °C after 2 h of filtration. In this work, the alumina-spinel composite hollow fibre membranes are found to be an effective tool as an alternative for the pretreatment of oily saline produced water.”	(Aziz et al., 2019)
8	*Facile fabrication of superhydrophobic and superoleophilic green ceramic hollow fiber membrane derived from waste sugarcane bagasse ash for oil/water separation*	“It was found that increasing the calcination temperature has degraded the sol template on the surface of ss-CHFM/WSBA, hence decreasing the wettability. The preliminary performance tests showed that ss-CHFM/WSBA grafted at 60 min, 3 cycles, and calcined at 400 °C showed excellent oil/water separation efficiency of 99.9% and oil flux of 137.2 L/m2h.”	(M. R. Jamalludin et al., 2020)
9	*Performance improvement of water and heat recovery from stripped gas in a carbon capture process: Assembling different pore-sized ceramic membranes in a transport membrane condenser*	“Results showed, among the five investigated TMC structures, where the stripped gas first contacted 100 nm membranes followed by 30 nm membranes demonstrated superior energy-saving potential in which the area ratio of 100 nm–30 nm membranes was maintained at 1:1 to 1:3. Notably, at a 1:1 area ratio, the TMC with 100 nm spaced by 30 nm membrane layout was achieved a maximum energy-saving potential of 0.94 MJ/kg-CO2, representing a 13.2 % increase over TMCs using only 30 nm membranes. Current finding offers a promising new direction for TMC structural design.”	(E. Wang et al., 2025)
10	*New ceramic membranes for tangential wastewater filtration*	The supports fired at 1190°C and characterised by mercury porosimetry showed pore diameters centred near 9.2 µm and porosity of about 50%. The water permeability measured for the membranes calcinated at 1000°C and with a mean pore size of 0.4 µm is 867 $1.h^{-1}.m^{-2}$.bar 1. These membranes can be used in tangential microfiltration.”	(Khemakhem et al., 2004)
11	*Preparation of corundum ceramic membrane with high permeability and corrosion resistance for oil-in-water separation*	“The resulting ceramic membrane exhibited a pore size of 0.25 µm, oil-water permeability of 4288.92 L/(m2 h bar), and an oil rejection efficiency exceeding 99 %. These findings highlight the potential of the developed ceramic membranes for efficient filtration in challenging environments.”	(Zhang et al., 2025)
12	*Evaluation of multi-*	“Moreover, single-channel membranes outperformed multi-channel	(R. Lee et al.,

	channel ceramic tubular membranes for high-salinity water desalination by vacuum membrane distillation	ones, demonstrating area-normalized fluxes as high as 39 kg/(m2 h) and NaCl rejections >99.5 % at 80 °C. The exponential increase in flux with temperature predicted by the Antoine equation was validated with a temperature-swing test up to 110 °C, where measured flux exceeded 200 kg/(m2 h). The performance and resilience of these ceramic membranes in treating brines across a range of temperatures demonstrate their viability for practical applications."	2025)
13	*Sustainable valorization of food waste into a pore-forming agent for ceramic membrane production: Experimental and DFT studies on methylene blue dye removal*	"The membrane had a negative surface charge at the pH >5.37, while the pH of MB was 6.17, implying adsorption as the removal mechanism for the cationic dye. This has been confirmed by DFT calculations. The dye removal for 20 mg L^{-1} feed concentration was 79 %, which increased to 86.1 % at pH = 10 and decreased to 74.26 % at pH = 2. The affordability of these ceramic membranes is attributed to the use of economical materials that don't need high sintering temperatures. The results of this research demonstrate that these membranes are both cost-effective and have favorable characteristics that make them suitable for water treatment purposes."	(Rakcho et al., 2024)
14	*Treating dyeing wastewater by ceramic membrane in crossflow microfiltration*	Compared with organic membranes, ceramic membrane has exceptional performance in cleaning and regeneration. The results show that the dynamic filtration equipped with a ceramic plate membrane as the filtration membrane has great advantages and a wide application future has been shown in membrane separation."	(Xu et al., 2002)
15	*Tape casting technique in the fabrication of ceramic membranes: A review of influential factors and applications in water and wastewater treatment*	"Tape-casted ceramic membranes showed significant potential in various fields, including fuel cells, desalination, and oily wastewater treatment. However, challenges remain, such as increasing output and improving cost-effectiveness, but ongoing innovation and optimization will propel the development of more effective and durable solutions for environmental and energy-related challenges."	(Esenli et al., 2025)
16	*Peat water treatment using biocoagulant and ceramic membrane*	"The results indicated that a dosage of 200 mg chitosan for 30 min achieved the highest removal of hybrid coagulation and ceramic membrane, removing 81.58 % COD, 89.5 % BOD, 29.11 % TDS, 66.81 % iron, and 73.85 % manganese, respectively. In addition, the pH increased by 33.89 %. SEM analysis revealed an increase in metal ions on the ceramic membrane surface. Researchers have demonstrated the effectiveness of ceramic membranes composed of silica sand, sawdust, and natural clay in separating organic matter from peat water. The results suggest that the combination of hybrid coagulation and ceramic membrane can produce clean water."	(Nasir et al., 2024)
17	*Remediation of industrial solid waste in the fabrication of porous alumina ceramic filter and their efficacy in aerosol filtration and the removal of oil from wastewater*	"The filters prepared using 20 wt% coal fly ash were found to be optimal and exhibited a flexural strength of 45.6 MPa at porosity of 40.8 vol%, and water permeability of 1084 LMH $bar^{-1,}$ and also showed good performance in the removal of oil and turbidity from oily wastewater. This work may appeal to the practical low-cost production of high-performance alumina ceramic filters with a wide range of potential applications."	(Ghosh et al., 2025)

18	*Removal of heavy metals from mine water using a hybrid electrocoagulation-ceramic membrane filtration process*	Under optimal conditions, EC removed over 95 % of Cr, Co, Cu, Fe, Mn, Ni, Pb, Ti, and Zn from the mine water. Effluent from EC was used as feed in the MF and UF processes with ceramic membranes. The tested membranes rejected 100 % of suspended solids from the EC effluent. Permeate from the membranes was free of solids and possessed turbidities of 0.05–0.15 NTU.”	(Atallah et al., 2024)
19	*Integrated cleaning of coloured wastewater by ceramic NF membranes*	“Due to the differences in the composition of the dyes, a decolouring of 70–100% was obtained. The fluxes varied between 0.2 and 1.l m^3/h, whereas the running costs were 0.50–2.80 DM/m^3 permeate, respectively.”	(Voigt et al., 2001)
20	*Preparation of whisker mullite ceramic membrane from coal fly ash for efficient oil-water separation*	Whisker mullite ceramic membranes were applied for deep treatment of oily wastewater. As-synthesized ceramic membrane exhibits excellent permeate flux (391.10 $L·m^{-2}·h^{-1}$) and oil rejection (97%) for the separation of O/W emulsion. The membrane fouling is mainly controlled by the cake filtration mechanism. Meanwhile, the ceramic membranes show good regeneration performance and acid and alkali resistance.”	(J. Gao et al., 2024)
21	*Super-hydrophobic ceramic membrane with dense and robust silane grafting for efficient water-in-oil emulsion separation*	“The ATP membrane grafted by HDTMS solution with a content of 9600 ppm for 24 h had a water contact angle of 161° and oil permeability larger than 2207.5 $L·m^{-2}·h^{-1}·bar^{-1}$ (LMHB). When dealing with W/O emulsions with a water content of 10000 ppm, the steady permeability, permeability recovery ratio, and water rejection of ATP-based HCM were 362 LMHB, 97 %, and 99 %, respectively. Ascribe to the –OH-rich nature of ATP, the performance of HCM in this work is superior to most membranes, including Al_2O_3, ZrO2, and SiC.”	(Z. Li et al., 2024)
22	*Oily-wastewater treatment using eco-friendly ceramic membranes derived from sugarcane bagasse waste: Optimization using response surface methodology*	“The three effective parameters analyzed were oil pH (3–11), oil concentration (10–10000 ppm), oil temperature (30–100 °C), and their combined effect to obtain high oil flux and excellent oil separation efficiency. Through the investigation, it was found that the optimum values of pH, oil concentration, and temperature were 10, 10.01 ppm, and 69.04 °C. The novelty of this study lies in the development of an eco-friendly ceramic membrane derived from sugarcane bagasse waste, offering an innovative and sustainable solution for oily-wastewater treatment.”	(N. Jamalludin et al., 2025)
23	*Heat and water recovery from a gaseous stream using a flat-sheet ceramic membrane as a transport membrane condenser*	“The highest TMC water recovery rate was 84.1%.”	(Le et al., 2024)
24	*Porous ceramic membranes fabricated mainly from red mud for oily wastewater treatment.*	“The steady permeate fluxes remain relatively stable at approximately 131.4 $L/(m^2·h·bar)$, and the oil rejections exceed 95.8 % (higher than 99 % in the vast majority of cases) during the recycling process (totally for 25 cycles, 3000 min). The membrane was further adopted for real wastewater (with a high oil concentration of 21.5 g/L)	(Z. Li et al., 2025)

		treatment. The results show that the membrane can intercept most oil droplets within the wastewater with an oil rejection as high as 80.7 % and with a steady permeate flux of 15.3 L/(m^2·h·bar)."	
25	*Efficient conversion from food waste to composite carbon source through rapid fermentation and ceramic membrane filtration*	"Ceramic membrane filtration can recover more than 70% of dissolved organic matter and more than 60% of small molecular organic matter and simultaneously remove 99% of SS, 41% of total nitrogen, and 62% of total phosphorus. At the rapid degradation stage, the denitrification rates reached 6.68–10.39 mg NOx−-N/(g VSS·h), which was on par with commercial carbon sources. The short fermentation and the rapid membrane separation were integrated to create an efficient treatment system, which provided a feasible pathway to utilize FW, combining wastewater treatment."	(Xiao et al., 2024)
26	*Sustainable valorization of electrocoagulation sludge in ceramic kaolinite membrane fabrication and its application to seawater pretreatment for SWRO desalination*	"The optimal membrane exhibited an average pore size of 1.43 µm, porosity of 39.30 %, permeability of 2580 L m^{-2} h^{-1} bar^{-1}, and mechanical strength of 21 MPa, demonstrating its suitability for microfiltration (MF) applications. MF tests of raw seawater confirmed the excellent pretreatment performance of the kaolinite/sludge membrane, achieving 95.24 % turbidity rejection, 81.14 % TOC removal, and 71.20 % COD reduction, while effectively lowering the SDI from 5.63 to 3.47. Fouling analysis revealed predominantly reversible cake layer formation, with up to 80 % flux recovery post-cleaning. The findings highlight the replicability and ecological potential of this approach for advancing sustainable desalination technologies."	(Belgada et al., 2025)
27	*Fabrication and characterization of low-cost ceramic membranes from coal fly ash and natural sand*	"The membrane showed a remarkable water permeability of 32.23 L/m^2/h. This study showed that natural sand and coal fly ash can be efficiently employed to develop a multifunctional filtration membrane with adjustable properties that can be utilized in water purification."	(Sawunyama et al., 2024)
28	*Low-cost ceramic membranes prepared from kaolin and quartz via tape casting using different pore formers.*	"Membranes with ~60 % porosity and water permeances of 1926–2646 L·m^{-2}·h^{-1}·bar^{-1} were obtained at 1300 °C using graphite. This study shows that adjusting slurry composition and sintering temperature enables the production of low-cost kaolinite-based membranes with tailored properties, expanding their applications in separation processes while reducing costs and environmental impact."	(Silveira et al., 2025)
29	*Low-cost ceramic membrane production for dye removal*	"The low-cost ceramic membrane was effective in separating blue methylene dye, with porosity of 53 % and average pore size of 0.48 µm, as well as pure water flow of 520 L/m^2.h. The blue methylene dye rejection was 100.00 %. The membrane reuse demonstrated good performance after 15 cycles."	(do Carmo et al., 2024)
30	*Highly efficient ceramic membrane synthesized from sugar scum and fly ash as sustainable*	The obtained ceramic membrane has a water permeability of 2356.68 L/h m2 bar, a pore size in the range 0–4.5 µm, and excellent chemical resistance in both acidic and basic media. Finally, the performance of the prepared ceramic membrane was evaluated by the filtration of	(El maguana et al., 2024)

	precursors for dyes removal	methylene blue. The results indicate that sugar scum and fly ash are suitable precursors to manufacture an effective ceramic membrane for the treatment of wastewater."	

5. Discussion

The reviewed paper thoroughly evaluates the efficacy of ceramic membranes in eliminating dyes and heavy metals from wastewater, pointing out both enduring difficulties and encouraging performance trends. Critical analysis of the findings highlights the versatility and great effectiveness of ceramic membranes, especially nanocomposites and hybrid designs, in a range of industrial applications. For instance, TiO_2-based ultrafiltration and nanofiltration membranes often obtain dye and metal removal efficiencies surpassing 95%, demonstrating their remarkable rejection rates (Solaiman et al., 2024; Chen et al., 2019). Notably, dyes with high fluxes and recyclability were best separated using loose nanofiltration (LNF) membranes. In contrast, removal efficiencies were greatly increased by hybrid techniques that combined ceramic membranes with electrocoagulation or distillation, reaching over 99% for metals such as Co^{2+} and Cr^{6+} (Atallah et al., 2024; Jiang et al., 2022). From an economic standpoint, using low-cost precursors like rice husk, sugarcane bagasse, and red mud has made ceramic membranes more affordable, although concerns about scalability persist due to the complexities involved in fabrication and the high temperatures required for sintering. Research involving waste-derived materials such as sugar scum and fly ash (El Maguana et al., 2024) has shown not only impressive chemical resistance and permeability but also environmental sustainability, which is vital for long-term implementation. Nevertheless, there remains variation in performance across different applications. For example, oil-water separation achieved over 95% efficiency at low pressure consistently (Wang et al., 2022), while the rejection of dyes varied significantly depending on the chemistry of the dye and the charge of the membrane surface (Rakcho et al., 2024). The effectiveness of dye removal through adsorption processes reveals a sensitivity to pH levels and contaminant concentrations, thus complicating standardization efforts.

Although polymeric membranes are more flexible and cost-effective in some situations, ceramic membranes are superior in terms of durability, heat resistance, and regeneration capability. Notably, ceramic membranes' exceptional antifouling qualities offer a significant benefit in high-load industrial environments where regular cleaning is necessary.

6. Conclusion

The literature reviewed demonstrates that ceramic membranes are very effective in eliminating heavy metals and dyes from wastewater, often achieving removal rates over 95%, particularly when combined with hybrid systems. Their durability, longevity, and resistance to fouling make them ideal for challenging applications, often surpassing polymeric membranes in various instances. Recent advancements in membrane production using waste materials have significantly lowered manufacturing costs while promoting environmental sustainability. However, problems including expensive initial prices, intricate fabrication procedures, and a lack of large-scale testing persist. As long as cost-effectiveness and validation for real-world uses are given top priority in future development, ceramic membranes present a viable and scalable alternative for advanced wastewater treatment.

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