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## Water Purification Employing Nanocomposites: Mechanism and Fabrication Strategies

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### ABSTRACT

Porous ceramic nanocomposites offer a combination of properties that most polymeric membranes cannot match: thermal and chemical durability from the ceramic matrix, and surface-level tunability from the nanoscale fillers. This review covers the fabrication strategies, purification mechanisms, and practical applications of these materials. Ceramic systems based on alumina, zirconia, silica, and titania are examined alongside nanofillers including carbon nanotubes, graphene oxide, metal oxides, and metal-organic frameworks (MOFs). Fabrication routes from conventional sintering and sol-gel processing through to electrospinning, atomic layer deposition, and additive manufacturing are assessed for their effect on pore architecture, surface chemistry, and transport behaviour. The purification mechanisms covered are adsorption, size-based sieving, photocatalytic degradation, and antimicrobial activity, including where these work together in nanocomposite systems. Performance across permeability, selectivity, fouling resistance, and chemical stability is compared against polymeric and monolithic ceramic membranes using laboratory, pilot, and commercial data. Applications in municipal and industrial wastewater treatment, desalination, oil-water separation, and decentralised systems are reviewed. Challenges that remain unresolved include fabrication cost, nanoparticle leaching, long-term durability, and regulatory compliance. Open research questions centre on green synthesis, stimuli-responsive designs, digital manufacturing, and integration with broader treatment systems.

### Introduction

Water pollution and the shortage of freshwater are significant environmental issues of the twenty-first century, posing risks to the ecosystems, human health and sustainable development. Rapid industrialisation, population increase, major agricultural practices, as well as poor management, have enhanced the pollution of surface and underground water resources. Drums of industrial effluents, residues of pesticides, pharmaceutical chemicals, and microbial wastes are often released into water bodies without proper treatment, which is gradually worsening the quality and availability of freshwater in most areas (Tripathy *et al.*, 2024). Climate change and unequal hydrological distribution of stresses further add to these stresses. The United Nations listed lack of freshwater among the key issues in the world, as close to two-thirds of the global population may face serious water shortages in the nearest future unless the current consumption trends and treatment approaches are changed (Hussein *et al.*, 2020). This situation is urgent, which explains the need to implement some sophisticated, robust, and resilient water purification measures that would help to overcome complicated contamination conditions.

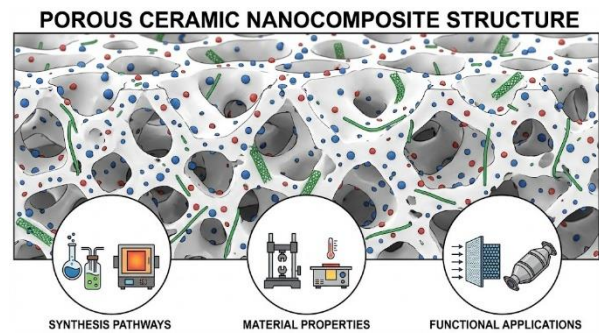
The water treatment technologies based on the membrane have received a great interest due to their high separation performance, relatively low energy demand and the ability to separate the

pollutants without a large-scale chemically supplemented treatment. Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are the methods that are effective in the removal of suspended solids, organic contaminants, microorganisms, and dissolved heavy metals (Al Harby *et al.*, 2022; Kolya *et al.*, 2023). Modularity, scalability, and flexibility of operation of membrane systems have made them easy to use in the municipal wastewater treatment and recovery of industrial effluents as well as decentralised purification systems. Moreover, hybrid treatment plans can be easily supplemented with membrane technologies in order to increase the overall performance of the process (Spoiala *et al.*, 2021). Regardless of these virtues, standard polymeric membranes have intrinsic constraints which limit their application in the long term, especially during demanding working conditions. Organic, inorganic, and biological species cause membrane fouling, which leads to the deterioration of flux, trans-membrane pressure, and regular washing that significantly increases operational expenses (Sahu *et al.*, 2023). In addition, polymeric membranes are often weak in terms of chemical, thermal, and mechanical stability, which makes them susceptible to deterioration, distortion, and stress during extreme industrial conditions (Sahu *et al.*, 2023).

Nanotechnology has widely been addressed in this regard as a way to improve the performance of the membrane in order to provide

nanocomposite membranes. Nanomaterials facilitate the interaction of the traditional membrane processability and the physicochemical peculiarities of the nanoscale additives (Tripathy *et al.*, 2024). Nanoparticles and nanostructures have a potential to increase permeability, selectivity, antifouling characteristics, and mechanical strength at the same time, enhancing the behaviour of resistance to chemical degradation (Al Harby *et al.*, 2022). In order to customise the membrane surface properties and increase the efficacy of contaminant removal, different nanomaterials have been considered, among which are metal oxides (TiO<sub>2</sub>, ZnO, and Fe<sub>3</sub>O<sub>4</sub>) and carbon-based materials (carbon nanotubes and graphene oxide) (Spoiala *et al.*, 2021). As an example, TiO<sub>2</sub> nanoparticles grant photocatalytic behaviour, which allows the breakdown of organic contaminants with ultraviolet radiation, and graphene oxide enhances the exposure of water surfaces and charge distribution, thus lessening foulness and increasing the flux of water (Satyam & Patra, 2024). However, the strength of performance improvement of nanocomposite membranes is closely related to the dispersion, interfacial compatibility, and long-term stability of the nanofillers in the membrane matrix. Poor mechanical dispersion or low interfacial bonding may impact the mechanical integrity and it may nullify performance improvement; therefore, the importance of careful material design and process control (Satyam and Patra, 2024). In this regard, it is possible to mention porous ceramic nanocomposites that have become a highly promising material in the context of the further development of the water purification process due to a great chemical, thermal and mechanical stability (Ewis *et al.*, 2021). Alumina, zirconia, silica and titania-trained ceramic membranes are more stable, offer greater resistance to fouling and maintain their stability under extreme operating conditions when compared to polymeric membranes. Their high-temperature stability, stability in harsh chemical conditions, and stability in high pressures make them highly suitable in industrial waste treatment and other methodologies that are more demanding (Hussein *et al.*, 2020). Ceramic membranes also differ compared to polymeric membranes in that they can withstand tough physical and chemical cleaning protocols, such as backwashing, ultrasonic treatment, and oxidative cleaning, without being structurally degraded. This regenerability increases the longevity of membranes, lowers downtime, and decreases operation cost hence increasing the sustainability of processes (Ewis *et al.*, 2021). In addition, unique and tuneable pore structure of ceramic membranes allows the efficient and selective extraction of particulates, dyes, microorganisms, and dissolved pollutants and the maintenance of reasonably advanced water fluxes (Tripathy *et al.*, 2024).

The further functionalisation of ceramic membrane work with nanomaterials contributes to the improvement of their performance, which is in the form of ceramic nanocomposite membranes with multifunctional features (Ewis *et al.*, 2021). Nanostructured reactions can be added to or coated onto ceramic structures to enhance reactivity, selectivity, and fouling resistance (Tripathy *et al.*, 2024). With photocatalytic and antimicrobial capabilities brought by the incorporation of TiO<sub>2</sub> or ZnO nanoparticles, contaminants to be removed through filtration and degradation can be conducted together. Similarly, hydrophilicity, permeability and mechanical toughness are enhanced by graphene oxide and carbon nanotubes, and antibacterial properties are enhanced by metallic nanoparticles like silver or copper, which are acceptable to pathogen-contaminated sewage (Satyam & Patra, 2024). Notably, ceramic nanocomposite membranes can offer the ability to reduce the traditional trade-off between transport selectivity and permeability by optimising nanomaterial loading and distribution to provide balanced transport functionalities and still maintain structural integrity (Sahu *et al.*, 2023). They are especially useful in wastewater streams that are difficult to treat, are highly porous, and highly mechanically rigid, and have a tailored surface chemistry (Al-Harby *et al.*, 2022).



Img: Illustrative structural image of Porous Ceramic Nanocomposites

The largest addition to the field of fabrication and material design in recent times has bolstered the promise of porous ceramic nanocomposites in next-generation technologies in water purification (Kolya & Kang, 2023). The attempts to reduce the costs associated with fabrication through the use of sol-gel processing, dip-coating, as well as use of naturally available raw materials and resources – kaolin and fly ash – have shown encouraging results (Tripathy *et al.*, 2024). The goals of these methods are to decrease energy use and material wastage and maintain high membrane functionality levels. As growing focus on the correlation of material formation with the principles of environmental sustainability has also favoured the creation of filtration systems with enduring and recyclable structures which have a minimum environmental impact (Hussein *et al.*, 2020). The long service life and low frequency of replacement of the ceramic nanocomposite membranes also contribute to the ideas of a circular economy by reducing the level of waste production (Kolya & Kang, 2023). In general, the available studies reveal that porous ceramic nanocomposites present an impressive development of water purification materials, offering a solid combination of momentum, chemical stability, and functionality as a variable. It is expected that, in the future, further advancements in this field will be critical to solve the problems of water scarcity and environmental pollution around the world and create harmless, sustainable, and stable water treatment models (Tripathy *et al.*, 2024; Ewis *et al.*, 2021; Hussein *et al.*, 2020).

### Fundamentals of Porous Ceramic Nanocomposites

#### Definition and Classification

Porous ceramic nanocomposites are engineered materials where a material (a ceramic) is combined with particulate-scale (nanoscale) reinforcements, such as a carbon nanotube, a material based on graphene, or a material based on metal oxide arrangements of both materials, or other functional nanoparticles, to create hybrid structures that cannot be obtained by either material alone (Chen *et al.*, 2021). These nanocomponents can either be microscopically distributed across the grains of the ceramic or concentrated at particular sites such as grain boundaries and pore walls with a correspondingly disproportionate effect on microstructural development, interfacial action and functionality. In addition to directly the boost of the reinforcement, nanoscale additive enables a much more finer control of porosity, surface chemistry, and mechanical response, extending the functional design space of ceramic materials (Barbaros *et al.*, 2022).

Poration of the ceramic nanocomposites has been widely classified based on the three categories that interrelate in nature with each other: type of ceramic matrix, morphology and chemistry of reinforcing nanomaterials and pore architecture. The typical ceramic matrices include alumina, zirconia, silica, titania and silicon-based ceramics; these have been chosen based on their thermal and chemical stability. Reinforcements can be addressed as nanoparticles, nanofibers, nanoplates, or nanotubes that bring about different effects that are controlled by geometry, aspect ratio, and contact with the ceramic structure (Hussein *et al.*, 2020). An example of this is that high-aspect-ratio reinforcements, e.g., carbon nanotubes, are the most effective at changing mechanical and transport reactions, but zero-dimensional nanoparticles are the most effective at affecting reactivity on surfaces and catalytic reactions.

The porous ceramic nanocomposites are further classified based on porosity distribution and hierarchy through microstructural classification. It is possible to have uniformly porous structures, graded porosity structures, and hierarchical porous structures that incorporate macro-, meso-, and micropores in a single material (Lu *et al.*, 2025). Hierarchical porosity is of particular benefit to uses where coupled mass transport and surface reactions are important: macropores used to allow fluid flow, mesopores for diffusion, and micropores for growth of active surface area. However, the problem of the exact control of multiscale porosity is still not completely achieved because the processes of pore formation are extremely dependent on the processing factors and the distribution of nanofillers.

As is defined by IUPAC, porous materials are categorised by their pore size as microporous (<2 nm), mesoporous (2–50 nm), and macroporous (>50 nm) (Barbaros *et al.*, 2022). Ceramic nanocomposites can be made porous so that they span either one or more of these regimes, and the control of pore size distribution is the key to their functionality in membrane filtration, catalysis, energy storage and biomedical applications. However, the parallel existence of pore connectivity, mechanical integrity and functional activity amongst various pore scales is also an important design challenge.

**Key Properties:** Porosity, Surface Area, and Chemical/Mechanical Stability

The high porosity and great specific surface area are the distinguishing features of porous ceramic nanocomposites. Porosity may be a few percentage of densified materials or higher porosity of foams or aerogel-like structures (Bodis *et al.*, 2022). The size of the pores can be between the millimetre and nanometre range and provide excellent control of the mass transport, adsorption kinetics, and catalytic accessibility. Membrane separation, heterogeneous catalysis, and bio-interfaces are two effects where surface interactions determine performance. In that regard, the subsequent high surface-to-volume ratios would be highly beneficial (Chen *et al.*, 2021; Bodis *et al.*, 2022). Nonetheless, extreme porosity may undermine the stability of the structure; hence, the role of balancing porosity with mechanical strength.

Ceramic nanocomposites are porous yet can be strongly mechanically reinforced and thus tough, in case they are suitably reinforced. Compressive strength, fracture toughness, and hardness can be increased with the incorporation of nanoscale additives, including carbon nanotubes or zirconia nanoparticles, in such a manner that it involves crack bridging, crack deflection, refinement of grains, and phase transformation toughening (Hussein *et al.*, 2020; Ewis *et al.*, 2021). The mechanisms reduce the brittle nature of porous ceramics and allow it withstand mechanical degradation due to operational stresses. However, mechanical improvement is very dependent on the dispersion of nanofillers and interfacial bonding, and poorly interconnected reinforcements can rather become the positions of a defect.

The other significant strength of porous ceramic nanocomposites is chemical and thermal stability. Ceramic matrices have inherent resistance to corrosion, oxidation and chemical attack, and such characteristics are normally augmented by the use of thermally and chemically stable nanofillers. As a result, ceramic nanocomposites are resistant to aggressive solvents, acidic or alkaline conditions, and high temperatures of operation and maintain the integrity of structure and functioning (Chen *et al.*, 2021; Bodis *et al.*, 2022). The ability to withstand thermal shock and their ability to sustain repeated thermal variations of heating and cooling without deteriorating their performance considerably make them most appealing to industrial applications which require changes in thermal conditions.

One of the strengths of the porous ceramic nanocomposites is their high tunability. The level of nanofiller loading, type of nanofiller and spatial distribution are functional properties which can be optimised by careful access without the need to change the sintering temperature, chemistry of precursor and pore-forming approach (Lu *et al.*, 2025). Through this design flexibility, end-use materials based on the application can be created, such as microfiltration

membranes as well as catalytic support and bioactive scaffolds. There is, however, a continuing difficulty in coming up with reproducible control of these parameters at larger scales.

**Comparison with Polymeric and Other Membrane Types**

Porous ceramic nanocomposites have unique benefits especially in harsh conditions of operating environment compared to polymeric membranes and other traditional membrane materials. Their high chemical and thermal stability enables them to work in conditions of high-strong acids and bases, organic solvents, and high temperatures in the environment, which will lead to swelling, degradation, or failure of the majority of polymeric membranes (Li *et al.*, 2020; Jarvis *et al.*, 2022). This increased operative range allows using hot-feed filtration, chemically aggressive wastewater treatment, and high-temperature catalytic separations (Arumugham *et al.*, 2021).

Mechanical strength also separates the ceramic nanocomposites and polymer-based systems further. The polymeric membrane is prone to deformation, creep, and fatigue when subjected to continuous pressure or cyclic weight, but ceramics nanocomposites do not change their dimensions after a long time of service (Li *et al.*, 2020; Jarvis *et al.*, 2022). Nanoscale reinforcements facilitate crack propagation and mechanical fatigue resistance, making them the appropriate materials to be used in high-pressure filtration and long-term industrial applications (Kotobuki *et al.*, 2021).

Lastly, ceramic nanocomposites membranes do not disintegrate during harsh cleaning and repair processes. It is possible to use high-temperature sterilization, chemical oxidation, and extended backwashing without damaging membrane integrity as polymeric membranes are likely to be damaged irreversibly under similar testing conditions (Kotobuki *et al.*, 2021; Li *et al.*, 2020). Such durability is converted to a primary result of increased service life, a lower frequency of maintenance, and enhanced process reliability.

However, there are no limitations related to ceramic nanocomposites. They tend to be harsher in general than the polymers and can be more difficult to fabricate using less energy or less expensive methods. Nevertheless, recent advances in the field of nanocomposite engineering, including additive-assisted sintering, bio-templating, and low-temperature processing, still help to eliminate these shortcomings (Jarvis *et al.*, 2022; Arumugham *et al.*, 2021). With the development of these methods, porous ceramic nanocomposites are becoming more competitive in the context of high performance as well as in the context of more wide-ranging industrial and environmental technologies.

**Fabrication Strategies for Porous Ceramic Nanocomposites: Methods and Impact on Performance**

There are an enormous variety of processing strategies that generate porous ceramic nanocomposites, and each has a decisive effect on pore structure, surface chemistry, mechanical integrity and finally on the performance of the membrane in either separation or filtration processes. The technology of fabrication, including both traditional high-temperature sintering and new methods of additive manufacturing and atomic-scaffolding deposition, has gradually increased the amount of control that can be exerted over the features of microstructure. As such, the fabrication strategy has become more than a processing step based strategy but is now an important design parameter that controls behaviour of transport, resistance to foul, as well as long-term durability. This part critically evaluates the known and new channels of fabrication, especially the influences of both methods towards effective performance of porous ceramic nanocomposites.

**Conventional Ceramic Membrane Fabrication Methods**

Sintering, sol-gel fabrication, tape casting, and phase inversion continue to dominate the traditional ceramic membrane fabrication. Such methods still support industrial-scale production of alumina-based, zirconia-based and titania-based membranes, as they are relatively simple, scalable and cost-effective compared to more complex methods (Coelho *et al.*, 2021; Yan *et al.*, 2025; Yu *et al.*, 2020). Even though they are mature, these approaches have specific benefits and drawbacks that directly affect the performance of the membrane.

Sintering is the process of shaping ceramic powders and then subjecting them to one sintering at high temperatures to give pore

networks that are interlocked and whose properties highly depend on the particle size, sintering temperature, and dwell time. An increase in sintering temperatures usually work well with developing an increase in mechanical strength in the form of growing and densifying of the grains at the cost of low porosity and low permeability. On the other hand, sintering with lower temperatures does not close porosity yet reduces the mechanical strength, which needs to be carefully optimised when high flux is needed along with maintaining structural integrity (Coelho *et al.*, 2021). This inherent trade-off highlights the drawbacks of sintering-based methods whereby one will require a fine control of pore size in applications.

Regardless of being polymeric or colloidal, sol-gel processing provides more control of microstructure by building ceramic network using molecular intermediates. By controlling the reaction of hydrolysis and condensation processes, sol-gel techniques can be used to create membranes whose pore structure is highly uniform and with a subtle pore-size distribution (Yan *et al.*, 2025). This type of membrane raises sol-gel-produced membranes to one that is especially useful in nanofiltration processes and catalytic processes. Nevertheless, the problems of shrinkage, cracking upon drying, and scalability are yet to be overcome to achieve popularity among industry users.

Tape casting is used extensively to make the ceramic membranes in flat sheets through casting of ceramic slurries, which contain binders and plasticisers. Tape casting, in combination with controlled drying and lamination, allows manufacturing asymmetric membranes with dense selective layers composed of more porous sublayers (Yu *et al.*, 2020). This design is selective and flux limited, although not all the interconnectivity between the pores can be under control and the formation of defects during drying can be a problem to reproducibility.

Phase inversion has been utilised traditionally to make polymeric membranes, but now can be made with ceramic membranes using ceramic-polymer composite precursors. Liquid-to-liquid demixing forms a porous polymer material which is then burnt to extract the polymer material to form a ceramic structure with well-developed pore structure (Coelho *et al.*, 2021). Combined with the technique of tape casting, phase inversion makes it possible to create multilayer ceramic membranes with graded porosity and enhanced mechanical stability (Yan *et al.*, 2025). Phase inversion, though versatile, adds another processing dimension and needs a lot of control to prevent pore collapse in the calcination process.

In total, the traditional techniques of fabrication are still indispensable because of their reproducibility and scalability, and their low power to adopt pore architecture and surface chemistry is an obstacle to additional performance improvement.

#### **Nanocomposite Integration Techniques**

The introduction of nanomaterials in ceramic membranes is one of the major efforts to conquer the inherent weaknesses of traditional ceramics. Membrane transportation, surface operation, and mechanical Behaviour can be altered by a significant amount using nanoscale reinforcements, including carbon nanotubes, graphene derivatives, metal-organic frameworks, and oxide nanoparticles (Naclerino *et al.*, 2025; Wang *et al.*, 2024; Zou and Fan, 2021). Nevertheless, the performance of nanocomposite design is highly dependent on the integration method used.

Direct synthesis Nanostructures may be directly synthesised in situ on or within ceramic substrates using in situ growth techniques. As a case study, carbon nanotubes can be chemically vapour grown on ceramic substrates to create vertically aligned networks of nanotubes or randomly piled nanotube networks. These constructions also increase mechanical strength and electrical conductivity and decrease antifouling on and off the structure in addition to minimising mass transfer resistance (Naclerio *et al.*, 2025). However, the large processing temperatures and poor scalability still serve as drawbacks to industrial practice.

The simplest and most common method of integration is that of blending, whereby nanoparticles like TiO<sub>2</sub> and ZnO or the graphene oxide are dispersed in ceramic slurries before casting or sintering. Although blending has the capability to improve hydrophilicity,

catalytic activity, and mechanical reinforcement significantly, uniform nanoparticle dispersion is quite challenging. The pore blockage or mechanical flaws may occur due to agglomeration, and it may require the use of surfactants or high-energy milling, compelling the incorporation of more complexity (Coelho *et al.*, 2021).

Surface functionalisation provides an approach to the addition of site-specific functionality without change of bulk microstructure. Especially polydopamine coatings are a universal type of adhesive layer surface, which enhances fixation of metal ions or nanoparticles onto the surface of ceramics (Wang *et al.*, 2024). These functionalisation approaches may include hydrophilicity, antimicrobial activity or increased selectivity, although durability on repeated clean cycles is another factor of consideration.

The layer-by-layer assembly also gives the ability to have fine control of the surface composition and thickness as well as thickness by the deposition of oppositely charged species one layer at a time. This method allows the nanometre-scale regulation of the properties of the membrane surface and can be most useful in increasing the membrane selectivity, antifouling and chemical resistance (Wang *et al.*, 2022). Nevertheless, the stepwise sliding/assembly characteristic of layer-by-layer assembly restrains throughput and potentially large-scale deployment (Gao *et al.*, 2023).

#### **Advanced and Emerging Fabrication Techniques**

Recent developments in nanotechnology have proposed methods of fabrication that offer more than ever before control of membrane structure and surface chemistry (Ye *et al.*, 2021; Sondhi *et al.*, 2025; Kacem *et al.*, 2025). Electrospinning is used to make ceramic nanofibrous mats that have extremely high surface area and interlacing pore structures. Further annealing produces recovered electrospun ceramic nanofibers with high permeability and catalytic capabilities; however, their mechanical weakness is still a challenge (Ye *et al.*, 2021).

Additive manufacturing, especially 3D based on digital light processing, allows the creation of intricate, hierarchised ceramic structures which cannot be produced by any other method of moulding. Networks of pores and designed and graded structures enable mechanically reinforced and fluid dynamics to be optimised at design (Kacem *et al.*, 2025). Although it promises, the reasons why it cannot be widely adopted are the equipment cost and low printing resolution, which is warranted as of now.

Atomic layer deposition and molecular layer deposition also allow an atomic level of control over surface coatings, which is employed to create a precise tuning of pore size, surface energy and chemical functionality in highly porous substrates (Sondhi *et al.*, 2025). Modifying the ceramic membranes with ALD increases the rates of selectivity, chemical stability, and resistance to foulages besides preserving the permeability (Nijboer *et al.*, 2024). However, low deposition rates and high processing costs are also limiting factors.

The development of nanostructured coating or the reinforcement of nanoparticles in place on ceramic surfaces has low-temperature energy-efficient paths through hydrothermal synthesis as well as SILAR. These methods permit crystallisation of nanostructures with controllability as well as towards photocatalyst and charge and transport purposes (Ding *et al.*, 2025).

#### **Influence of Fabrication Strategy on Structure and Performance**

Pore size distribution, connectivity, and tortuosity, as well as surface chemistry are all the parameters that regulate the strategy of fabrication and ultimately determine permeability, selectivity, foulant resistance, and mechanical stability (Sondhi *et al.*, 2025; Zou and Fan, 2021). Traditional sintering facilitates mechanical strength but provides a low level of pore uniformity, and sol-gel processing, electrospinning, and ALD provide much more control over both the size of the pore and the surface chemistry, but at the cost of scalability.

The interfacial interactions are largely effected by surface-oriented methods, including layer-by-layer assembly, functionalization, which alleviate the foulings and improve the solute selectivity (Wang *et al.*, 2022; Gao *et al.*, 2023). Conversely, the 3D printing makes structural optimisation on the macroscopic scale possible,

thus allowing membranes to be engineered to meet localised hydrodynamic and mechanical demands (Kacem *et al.*, 2025). On a small scale, the application of atomic-layer deposition is a process that can uniquely be used to form ultrathin selective depositions of material to remove additional transport resistance enhancing separation efficiency (Nijboer *et al.*, 2024).

Finally, the fabrication strategy does not only control membrane structure but also long term operating life. It is only the thorough knowledge and utilization of these fabrication structure performance interrelations that will allow the rational design of the next-generation porous ceramic nanocomposites compatible with the real-world water treatment usage.

Method	Key Features	Pros	Cons	Performance Impact	Refs
Sintering	High-temp powder consolidation	Strong, scalable	Limited nanoscale control	Robust macroporous structures	Coelho 2021
Sol-Gel	Molecular precursor gelation	Uniform, tunable pores	Drying shrinkage	Ideal for micro/mesoporous membranes	Yan 2025
Tape Casting	Thin ceramic tapes	Asymmetric structure; scalable	Binder burnout needed	High flux, graded porosity	Yu 2020
Phase Inversion	Ceramic – polymer demixing	Tunable porosity	Potential defects	Asymmetric, high-permeability membranes	Coelho 2021
In-Situ Growth	Nanomaterial formation on ceramics	Strong interface, functional	Costly, equipment-heavy	Enhanced strength, antifouling	Naclerio 2025
Blending	Nanoparticles mixed in slurries	Simple, multifunctional	Agglomeration risks	Improved strength, activity	Coelho 2021
Surface Functionalization	Chemical surface modification	Better wettability, adhesion	Coating stability issues	Reduced fouling, improved selectivity	Wang 2024
LBL Assembly	Sequential charged-layer deposition	Nanoscale precision	Time-intensive	Strong selectivity, antifouling	Wang 2022 ; Gao 2023
Electrospinning	Ceramic nanofiber mats	High surface area	Careful calculation needed	High flux, fast transport	Ye 2021
3D Printing	Architected ceramics (DLP)	Customizable structures	Resin/material limits	Engineered pore networks	Kacem 2025
ALD/MLD	Atomic-scale coating	Precise chemistry/pore control	Slow, equipment-heavy	Superior selectivity/stability	Sonhi 2025 ; Nijboer 2024
Hydrothermal	Aqueous nanostructure growth	Low-temp, crystalline	Limited scale	Enhanced catalytic surfaces	Ding 2025
SILAR	Layered ionic	Energy-efficient	Slow, adhesion	Improved photocatalytic/	Ding 2025

**deposition**      **varies**      **functional surfaces**

**Table 1: Fabrication Strategies for Porous Ceramic Nanocomposites**

**Mechanisms of Water Purification in Porous Ceramic Nanocomposites:** Adsorption, Sieving, Photocatalysis, and Synergy

Porous ceramic nanocomposites have been discovered as a significant line of further-generation material for water purification because of their remarkable structural integrity, adjustable porosity, and their ability to be improved in functionality with the addition of nanoscale materials. The capability of porous ceramics to incorporate metal oxides, carbon nanostructures, clays, and metal-organic frameworks (MOFs) has made it possible to integrate several water treatment processes, including adsorption, size-based sieving, photocatalysis, and antimicrobial activity in a single membrane or filter. These combined processes offer wide purification scientific abilities that tackle the growing, intricate compositions of wastewater and natural waters. An effective mechanistic perspective of the way the porous ceramic nanocomposites eliminate contaminants is thus critical towards logical material design, optimisation, and utilisation within the water treatment systems of the future that are sustainable.

**Adsorption Pathways for Metals, Dyes, and Organic Pollutants**

Due to their large surface areas on the inner surfaces, designed surface chemistry and existence of nanoscale strengthening materials which enhance the number of active binding sites, adsorption has remained one of the most prevalent purification pathways in porous, ceramic nanocomposites. The adsorption affinity of ceramics to several types of contaminants, including heavy metals, pharmaceutical residues, and many other contaminants, is enhanced significantly by the nanomaterials, which include graphene oxide (GO), MOFs, clays, ZnO, and other functional oxides (He *et al.*, 2023; Moyo *et al.*, 2022; Soltani *et al.*, 2020).

**Removal of Heavy Metals**

The persistent pollutants of great environmental concern are heavy metals, such as Cr(VI), Cr(III), Pb(II), Cu(II) and Cd(II). These elements are toxic and bioaccumulating. GO-strengthened ceramics, hybrids between clay and ceramics, as well as membranes based on MOFs, have great uptake capabilities of metals. Dominating metal adsorption processes are:

- Electrostatic interactions between positively charged metal ions and negatively charged ceramic or GO surfaces (Moyo *et al.*, 2022).
- Surface complexation, the coordination of metal ions and oxygenated groups on the surface of the surfaces of GO or oxide (-OH, -COOH, -O-COOH, -O-O) (He *et al.*, 2023).
- Ion exchange, especially in nanocomposites including clay or MOF fillers, in which the case of lattice ions being replaced by metal cations (Kolya & Kang, 2023).
- Redox reactions, particularly to such contaminants as Cr(VI), which would be reduced to less harmful Cr(III) when subjected to the influence of photocatalytic nanofillers (Soltani *et al.*, 2020).

These mechanisms can be utilised synergistically on nanocomposite matrices, leading to the elimination of certain efficiencies often reaching 90-99 per cent of the usual heavy metals of its type (He *et al.*, 2023; Soltani *et al.*, 2020).

**Adsorption of Dyes and Industrial Organics**

Organic pollutants (e.g., phenolics, antibiotics, pharmaceuticals), along with industrial dyes (e.g., methylene blue, rhodamine B, Congo red), are difficult to eliminate using conventional methods based on their solubility and size. Some of the binding pathways included in ceramic nanocomposites include:

- $\pi$ - $\pi$  interactions with carbonaceous nanofillers, including GO or CNTs of aromatic dye molecules (Moyo *et al.*, 2022).
- Hydrogen bonding of dye molecules with hydroxyl-rich surfaces of ceramics or MOFs.
- Van der Waals interactions between porous ceramic structures.
- Enhanced hydrophilicity, which augments the incorporation of dissolved organics into the network of pores (Qiu *et al.*, 2023).

Hybrid composites, which incorporate the entity of GO, metal oxides, and MOFs, usually exhibit a higher adsorption capacity and selectivity of pollutants. One example is MOF-ceramic membranes

that have high coordination with dye molecules and pharmaceuticals because they are featured with metal nodes and porous organic linkers (Soltani *et al.*, 2020).

### Synergistic Adsorption Enhancement

The ceramic matrix and nanofiller synergy are an imperative one. Porous ceramics provide mechanical stability and chemical resistance, whereas nanofillers provide active sites and functional groups of high affinity. GO enhances the number of oxygenated sites per square gram as well as the degree of surface densities. MOF offers ultrahigh performance in microporosity and programmable metal-ligand. Clay nanomaterials provide cation-exchange abilities (Kolya and Kang, 2023). These multi-component interactions lead to composite adsorbents that can eliminate various groups of contaminants at the same time.

Size Exclusion and Sieving for Particulates, Microorganisms, and Viruses

An intrinsic purification process of porous ceramic membrane is size-based exclusion, because the pore structure can be tuned, either macropores (> 50 nm) or nanopores (< 10 nm). Ceramics are rigid and chemically stable, which means that the membranes can be used at high pressure, high temperature, and under chemically hostile conditions that polymeric membranes normally cannot survive (Bahadi *et al.*, 2024; Ma *et al.*, 2021).

### Microfiltration and Ultrafiltration Regimes

Microfiltration with ceramic nanocomposites has pores of a size (between 0.1 and 10  $\mu\text{m}$ ) that allow the removal of:

- suspended solids
- protozoa
- bacteria
- colloidal particles

Ultrafiltration membrane with pore sizes of 2-100nm filters:

- viruses
- proteins
- biopolymers
- microplastics (Bahadi *et al.*, 2024)

Hydrophilicity can be dramatically improved by the introduction of nanofillers (e.g., ZnO, CNTs, GO) into ceramic matrices and narrow down or uniform pore size distributions to increase flux and selectivity at the same time (Moyo *et al.*, 2022).

Nanofiltration and Selective Nano-Sieving

Ceramic nanocomposites with ultrathin selective layers based on nanopores less than 2 nm or controlled nanochannels are used in nanofiltration. Of particular interest are the carbon nanotube (CNT) nanocomposites, which involve the introduction of fast transport channels with a high slip length. These nanochannels permit fast water flow whilst preserving a high size-based exclusion of:

- viruses
- multivalent ions
- small organic molecules (Ma *et al.*, 2021; Zhang *et al.*, 2023)

Moreover, surface charge plays a significant role. Negatively charged ceramics repel similarly charged solutes, improving rejection of dyes and organic acids (Zhang *et al.*, 2021).

Hierarchical Multi-Level Sieving

Nanocomposites with hierarchical porosity include many high-performance nanocomposite membranes, including:

- Macroporous supports (structural integrity and low flow resistance)
- Mesoporous interlayers (enhanced water distribution)
- Nanoporous selective layers (precise contaminant sieving)

The architecture has a maximum degree of water permeability, and the contaminants are rejected (Bahadi *et al.*, 2024; Zhang *et al.*, 2021). Hierarchical design is also effective in reducing resistance to fouling and compressive forces.

### Photocatalysis and Advanced Oxidation Mechanisms

Photocatalysis offers an effective oxidative purification platform in the ceramic nanocomposites with semiconductor nanoparticles, including TiO<sub>2</sub>, ZnO, ZnS, WO<sub>3</sub> and MOF-derived photocatalysts (Abukhanafer *et al.*, 2025; Li *et al.*, 2025). The materials produce reactive oxygen species (ROS), and they can degrade all types of recalcitrant organics.

Fundamental Photocatalytic Pathways

Upon the irradiation of photocatalysts:

1. Photons cause electrons to be excited to the conduction band.
2. electron-hole ( $e^-/h^+$ ) pairs form
3. The reaction of the electrons and holes with water or oxygen dissolved results in the generation of ROS, including:
  - a. hydroxyl radicals (OH $\cdot$ )
  - b. superoxide radicals ( $O_2^{\bullet-}$ )
  - c. hydrogen peroxide ( $H_2O_2$ )
  - d. singlet oxygen

They are species that can break down dyes, pesticides, phenols, pharmaceuticals, and even cell membranes of microbes indiscriminately using them as their fuel (Kanakaraju *et al.*, 2023).

### Photocatalytic Nanocomposite Systems

The porous ceramic matrices offer the best avenues of distributing the photocatalysts since they eliminate agglomeration, enhance photon absorption, and enable the pollutants to access the catalytic sites (Abukhanafer *et al.*, 2025).

Hybrid photocatalysts such as TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub>, TiO<sub>2</sub>/ZnS, and MOF-TiO<sub>2</sub> exhibit significantly enhanced activity due to:

- reduced electron-hole recombination
- enhanced visible-light absorption
- synergistic catalytic interfaces (Li *et al.*, 2025; Kobkeathawin *et al.*, 2022)

These characteristics render the ceramic composite photocatalysts particularly effective in destroying the hard-to-boil pollutants and pathogens.

### Pathogen Inactivation through Photocatalysis

The antimicrobial effects of photocatalytic nanocomposites are also very strong. The produced ROS attack microbial membranes, proteins and nucleic acids, resulting in cell death. Ceramics based on TiO<sub>2</sub>, specifically, exhibit a strong antibacterial, anti-viral and algae-inactivation effect (Kanakaraj *et al.*, 2023).

### Antimicrobial and Antifouling Behaviours

One of the most important problems of the membrane processes is fouling, and the antimicrobial and antifouling functions are implemented in the ceramic nanocomposites in a strategic way to reduce the decline in performance.

Metallic and Metal Oxide Nanoparticle Antimicrobials

Nanoparticles such as Ag, Cu, ZnO, and TiO<sub>2</sub> exert antimicrobial effects through:

- ROS generation
- membrane disruption
- leakage of cellular contents
- DNA damage

Silver and copper nanoparticles are particularly useful in the context of broad-spectrum antimicrobial agents with the ability to prevent biofilm formation (He *et al.*, 2023; Ma *et al.*, 2021).

Hydrophilic Surface Engineering and Anti-Adhesion

Foulant reduction of adhesion is achieved by increasing the hydrophilicity through GO, polydopamine (PDA), or hydrophilic metal oxides. Hydrophilic surfaces attract the formation of water layers, and this serves as a barrier that prevents organic molecules and microorganisms from attaching. Other effects of GO-modified ceramic membranes are the much less than usual organic fouling provided by improved hydration brushes (Moyo *et al.*, 2022; Ewis *et al.*, 2021).

Another beneficial aspect of superhydrophobic changes is the possibility to use it in oil-water separation or anti-bioadhesion (Qiu *et al.*, 2023).

### Self-Cleaning and Photocatalytic Antifouling

Organic foulants. On light exposure, photocatalyst-integrated membranes degrade foulants by the generation of ROS. The given self-cleaning is the type that minimises the maintenance and prolongs the membrane life (Li *et al.*, 2025; Abukhanafer *et al.*, 2025).

### Mechanistic Synergy and Enhanced Purification Performance

The interaction capacity of porous ceramic nanocomposites as a means of integrating various purification mechanisms is the most crucial property. Unlike the conventional membranes, which are mainly based on size exclusion, nanocomposite ceramics embrace adsorption affinity, photocatalytic degradation, antimicrobial

activity, and hierarchical sieving together to yield better and extended results of purification.

Integration of Adsorption, Sieving, and Photocatalysis

A single membrane may:

- adsorb heavy metals and dyes
- strains particulates, viruses and bacteria.
- stabilise organics through a UV or sunlight photocatalytic reaction.
- Fouling can also be mitigated using hydrophilic nanomaterials or antimicrobial nanomaterials.

Multifunctional work is typically impressive because TiO<sub>2</sub>-GO-ceramic nanocomposites, such as those, have great adsorption capacity, superior photocatalytic degradation, and antimicrobial growth (Kolya and Kang, 2023; Qiu *et al.*, 2023).

Long-Term Durability and Operational Advantages

Ceramic nanocomposites are vigorous and thus exist:

- long operational lifetimes
- bendable diffusive flow at constant pressure.
- resistance to acids or oxidation, Chemical stability in acidic or oxidative conditions
- low energy consumption.
- downplayed the cleanliness rate.
- similar rejection in an environment of changeable feed conditions (Zhang *et al.*, 2021; Soltani *et al.*, 2020)

This makes them suitable for decentralised treatment, factory wastewater reuse and high-stress purification conditions.

Broad Spectrum Contaminant Removal

These mechanisms, when combined, provide the nanocomposites with an ability to target:

- heavy metals
- dyes
- pharmaceutical residues
- persistent organic pollutants
- bacteria and viruses
- endocrine-disrupting compounds
- microplastics
- oils and emulsions (Al Harby *et al.*, 2022)

The high-level capabilities of such complex wastewater streams with organic, inorganic, and biological contaminants of different mixtures are especially appropriate in the case of ceramic nanocomposites.

### Performance Evaluation of Ceramic Nanocomposite Membranes: Metrics, Protocols, and Comparative Insights

The study of ceramic nanocomposite membranes requires a progressive analysis of transport characteristics as well as separation effectiveness resistance to fouling as well as stability of ceramic membranes over time in conditions that are both standardized and specific to applications. Compared with the traditional polymeric or monolithic ceramic membrane, the ceramic nanocomposites incorporate both the natural strength of ceramic composites and regulate the surface and transport characteristics appropriately through the addition of nanoscale materials. As a result, their performance indices are often over and above those of conventional membranes, more so when there is chemical aggression or higher-temperature conditions. Nevertheless, all these improvements are not natural, and they require extensive reliance on composite design, fabrication strategy, and functionalising the surface (Li *et al.*, 2020; Ewis *et al.*, 2021; Sun *et al.*, 2024). The critical assessment of key performance indicators is thus required to notice between the actual material improvement and the gradual one.

#### Key Performance Metrics Permeability and Flux

Primary indicators of productivity in the processes based on pressure are permeability and water flux. The intrinsic expression of the ease at which water passes through the membrane under an applied pressure is permeability, and the expression of the operational rate in units of membrane area is flux. Their parameters in ceramic nanocomposite membranes can be controlled by pore size distribution, porosity, tortuosity, surface hydrophilicity, and the spatial distribution of nanofillers. Notably, the increased permeability is usually the result of higher surface wettability

yielding a reduced transport resistance but not the increase of the pore size.

Factors like sintering temperature, heating rate and nanomaterial addition are decisive parameters of fabrication. Reduced sintering of materials shows preservation of porosity with the associated costs of reduced mechanical integrity, whereas nanorandom-resistant materials like graphene oxide or metal oxides can offset this cost through enhanced hydrophilicity and pore wall stabilisation. The permeability values of the porous ceramic membranes with regulated pore architectures are reported in the range of 41.58–45.86 L m<sup>-1</sup> h<sup>-1</sup> bar<sup>-1</sup> (Hussein *et al.* 2020) and indicated similar or better permeability with nanocomposite modification (Ma *et al.* 2024). These results indicate that the design of nanocomposites allows permeability to be increased without the drastic strength and porosity trade-off characteristic in traditional ceramics. However, load overshoot may result in a blockage of pores or higher tortuosity in nanofillers, and optimisation should be the key improvement.

#### Selectivity and Rejection Rates

Selectivity (often defined as contaminant rejection efficiency) is the capacity of a membrane to selectively exclude solutes of various size, charges and even chemical affinities. Membranes of ceramic nanocomposites often have rejection rates of over 94 per cent of heavy metals, dyes and target inorganic ions (Ewis *et al.*, 2021; Sun *et al.*, 2024). The causes of these high rejection values are a mixture of size exclusion, electrostatic (Donnan) interactions, and selective adsorption that is brought about by nanomaterials like graphene oxide, metal-organic frameworks, or metal oxide nanoparticles.

Compared to polymeric membranes, where high selectivity is typically achieved at the price of decreased flux, nanocomposites of ceramics can either decouple this trade-off by reducing the size distributions of pore sizes or placing charge on the surface without making hydraulic resistance increase significantly. Molecular weight cut-off is still an objective standard to assess the performance of nanofiltration (Kotobuki *et al.*, 2021), and nanocomposite modifications have been demonstrated to reduce effective MWCO without impacting permeability. Nevertheless, prolonged stability of surface charges and adsorption sites in sustained operation is not well studied in a number of studies, thus restricting predictive analysis of membrane life duration.

#### Fouling Resistance

Resistance due to fouling is a highly sensitive factor that defines the sustainability of operations and financial feasibility. Ceramic nanocomposite membranes tend to perform better than polymeric membranes in terms of fouling resistance due to their natural hydrophilicity, chemically resistant surfaces, and acceptance of violent cleaning schemes. Organic adsorption is inhibited, and inorganic scaling is inhibited through incorporation of hydrophilic nanofillers like TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> or graphene oxide, which enhances hydration layers and foulant-to-surface interactions (Li *et al.*, 2020; Ewis *et al.*, 2021).

Yang *et al.* (2021) reported that nanostructured functionalised ceramic membranes with oxide exhibited sustained flux with prolonged periods of filtration under little irreversible fouling. Moreover, irradiation under photocatalytic nanofillers like TiO<sub>2</sub> can produce reactive oxygen species, giving them an antimicrobial and antibiofouling effect. Although these effects are very promising, external activation (e.g., UV light) and possible degradation of surface coats cast some doubts on the consistency of long-term performance in real-world systems.

Standardised Testing Protocols and Real-World Relevance

#### Laboratory-Standard Protocols

Healthy and fundamental protocols of testing ensure that there can be performance evaluation and the meaning of comparison between studies. Porosity and mechanical properties are generally evaluated according to ASTM standards such as open porosity and water absorption (Hussein *et al.*, 2020). Dead-end or crossflow modified filtration is done with permeability and flux being measured at controlled transmembrane pressure, and fouling resistance happening through flux recovery ratio, normalised flux decay, and repeated filtration-cleaning cycles (Ma *et al.*, 2024).

These guidelines allow systematising the testing of nanocomposite modification and chemical or thermal load. But during testing on laboratory scales, simplified solutions of feeds are commonly used and may not represent much of the fouling complexity as well as the competitive adsorption effects observed in actual wastewater.

#### Evaluation Under Real Wastewater Conditions

The assessment of performance under the realistic wastewater conditions is becoming more and more important. Industrial effluents, saline streams, and complex mixtures with oils, surfactants, and heavy metals have been investigated by studies that show that ceramic nanocomposite membranes are capable of keeping their rejection rates at or above 90.0 per cent and that the flux is consistent (Ewis *et al.*, 2021; Yang *et al.*, 2021). They lose their chemical and thermal shock stability, which allows them to operate in conditions that easily corrupt polymeric membranes, making them useful in the treatment of textile wastewater, petrochemical effluent polishing and metal ion recovery (Sun *et al.*, 2024). However, field-scale validation that supports long times is still restricted, and how wastewater varies also challenges its capability to predict performance.

#### Comparative Analysis with Other Membrane Technologies

##### Ceramic vs. Polymeric Membranes

Ceramic nanocomposite membranes have excellent chemical, thermal, and mechanical stability, fouling and harsh cleaning regime resistance over polymeric membranes (Li *et al.*, 2020; Kotobuki *et al.*, 2021). Their resistance to acidic, alkaline and oxidative cleaning greatly increases the time of operation. Nevertheless, the cost of a material and fabrication is still a major obstacle to general integration, especially in low-pressure and low-cost instances where polymeric membranes can still compete.

##### Performance Enhancements through Nanocomposite Engineering

Nanocomposite engineering also makes it possible to overcome the constraints inherent to both traditional ceramics and polymeric systems in the form of ceramic membranes. Nanomaterials that help to increase flux, selectivity, antimicrobial activity, and fouling resistance include TiO<sub>2</sub>, carbon nanotubes, graphene oxide, and metal-organic frameworks (Ewis *et al.*, 2021; Yang *et al.*, 2021). On the one hand, Sun *et al.* (2024) indicated that TiO<sub>2</sub>-based ceramic nanocomposites retained high flux and experienced less degradation after several filtration cycles than unmodified ceramic membranes. Such findings highlight the possibilities of the nanocomposite approach to create long-lasting, high-performance membranes, assuming that the issues of cost, scale, and sustainability in the long term can be dealt with.

Metric	Ceramic Nanocomposite Membranes	Polymeric Membranes	10.0 References
Permeability / Flux	High and tunable based on porosity, nanofillers, and sintering	Moderate to high, depending on polymer type	Li <i>et al.</i> , 2020; Hussein <i>et al.</i> , 2020; Ma <i>et al.</i> , 2024
Selectivity / Rejection	Typically, >94% for metals, dyes, salts	Variable; often lower, especially under harsh conditions	Ewis <i>et al.</i> , 2021; Sun <i>et al.</i> , 2024; Yang <i>et al.</i> , 2021
Fouling Resistance	Superior, with high flux recovery	Moderate to poor	Li <i>et al.</i> , 2020; Ewis <i>et al.</i> , 2021; Yang <i>et al.</i> , 2021
Chemical Stability	Excellent at extreme pH and temperature	Limited; susceptible to degradation	Kotobuki <i>et al.</i> , 2021
Cost	Higher fabrication and material costs	Generally lower	Kotobuki <i>et al.</i> , 2021

**Table: Performance Metrics and Comparative Insights**

#### Applications of Ceramic Nanocomposite Membranes in Water Treatment

Ceramic nanocomposite membrane materials have become one of the most flexible water purification techniques because of their high stability, levels of selection, and capacity to withstand fouling. Such membranes are more efficient than several traditional polymeric systems, particularly in chemically or thermally hostile conditions, upon introducing the intrinsic benefits of ceramic substrates and

additives to create high-performance functional nanoscale fillers. They have already been used in municipal wastewater treatment, industrial effluent removal, desalination, oil-water separation and point-of-use systems (decentralised). Their reliability and wide-ranging use are still proven by recent laboratory research, pilot projects, and commercial use (Sun *et al.*, 2024; Li *et al.*, 2021).

#### Municipal and Industrial Wastewater Treatment

Municipal and industrial waste discharges usually have a variety of contaminants such as heavy metals, dyes, pharmaceuticals, endocrine-disrupting chemicals and many other emerging pollutants. The use of ceramic nanocomposite membranes is a potent remedy for the treatment of these complex matrices since they have high chemical permeability, long lifespan of operation, and a high level of rejection. Many studies describe the removal of such metals (cadmium, lead, copper, and chromium) greater than 90 per cent and the removal of dyes (methylene blue, rhodamine B), antibiotics, and aromatic organics (Ewis *et al.*, 2021; Hussein *et al.*, 2020; Zhang *et al.*, 2023).

Nanomaterials, including TiO<sub>2</sub>, graphene oxide, metal oxides and metal-organic frameworks (MOFs) incorporated between the ceramic matrices, increase the reactivity of the surface, adsorption performance, and catalytic degradation performance. As an example, Li *et al.* (2021) have shown that nanocomposite ceramic membranes were stable in rejecting pharmaceuticals that are challenging to eliminate with polymeric membranes. Notably, performance is maintained under long-term continuous filtration, and this is explained by the fact that the membrane is resistant towards chemical degradation and that it can be cleansed by using strong oxidants or acids, an option that cannot be used in polymeric systems.

In addition to single-stage filtration, the combination of ceramic nanocomposites with the advanced oxidation processes (AOPs) further increases the results of the treatment process. Using ozonation with ceramic nanocomposite membranes has demonstrated much better pharmaceutical, microplastic, and trace organic contaminant mineralisation through the enhancement of hydroxyl radical production at the surface of the membrane (Fu *et al.*, 2023; Xie *et al.*, 2024). These hybrid systems provide effective responses to treating wastewater with long-lasting pollutants that allow further increases in the quality of effluents that can be reused.

#### Desalination and Brackish Water Treatment

Nanocomposite membranes made from ceramics are gradually being used in the field of desalination, especially nanofiltration (NF), reverse osmosis (RO) and forward osmosis (FO), because they are superior in terms of chemical and thermal stability. The properties render them applicable to tough conditions experienced during the treatment of brine, pre-treatment of seawater, and treatment of industrial desalination processes.

Innovations that include MOF interlayers and nanocomposite thin-film coating have largely improved membrane properties. The researchers Alhoshan *et al.* (2022) found that better flux and salt rejection in nanocomposite NF membranes were achieved because of increased hydrophilicity and optimal nano-channel pathways formed by the MOF layer. Another advantage noted by Sun *et al.* (2024) was that RO membranes with polymer had lower fouling and worse chlorine resistance. All these benefits give ceramic nanocomposites the ability to be used as a robust pre-treatment coating, enhancing the load utilised by the downstream RO units and improving the overall efficiency of the plants.

Notably, ceramic nanocomposite FO membranes are highly stable in high saline brine and draw solutions that would easily degrade polymeric membranes. This renders them viable in terms of desalination in the petrochemical industries, mining industry and textile industries (Cabrera *et al.*, 2021).

#### Oil–Water Separation

Among the most promising uses of ceramic nanocomposite membranes are oil-water separation, particularly in petrochemical, food processing, metallurgy, and offshore exploration industries. Superhydrophobic and superoleophilic-coated membranes demonstrate high separation efficiencies of above 99%, even when the droplets of the emulsified oil or the surfactant is present

(Sutrisna *et al.*, 2024; Agtas *et al.*, 2020). Selective wettability Nanocomposite layers, usually containing graphene derivatives, TiO<sub>2</sub> nanoparticles or other fluorinated coverings, are used to enable water to enter and oil to leave.

The mechanical stability of these membranes, coupled with an immune state to the chemical solvents, enables the membranes to maintain their performance after several cycles. Zhang *et al.* (2023) obtained the stability of the separation performance in extreme conditions of pH and temperature, and then this is appropriate to be used in industrial conditions. The fact that it is possible to regenerate the membranes by thermal or chemical cleaning also makes them long-term viable.

#### Point-of-Use and Decentralised Water Purification

Ceramic nanocomposite membranes are suitable for point-of-use (POU) and decentralised water treatment through the strength and prolonged lifespan of the membranes applied. In remote locations or resource-constrained environments, they should have durability, as they may have limited maintenance opportunities. According to Zhang *et al.* (2023), POU filters made of ceramics always eliminate pathogens or particulates and heavy metals without any performance decline after prolonged operation in the field. Their anti-biofouling and anti-breakage properties are superior compared to polymeric filters that are normally applied in domestic systems.

The additional benefits of nanocomposite functionalisation are related to the facilitation of antimicrobial functions, which would add to the safety and reliability of rural water supplies, emergency response systems, and mobile purification equipment.

#### Case Studies and Commercialisation

Pilot-scale tests and commercial implementations are strong cases that the ceramic nanocomposite membranes are effective in practice. Indicatively, oil sands mine water recycling with ceramic nanocomposite modules has been demonstrated to reach high filtration levels of suspended solids, dissolved organics, and surfactants, and high flux was sustained over a long period (Cabrera *et al.*, 2021). Nanocomposite ceramic membranes have also become the new tool of textile wastewater treatment facilities, where they are used to remove dyes and salts so that the water may be reused in the process and less freshwater may be used (Xie *et al.*, 2024).

These membranes are now being introduced in industrial applications as modular units of filtration in commercial systems when used in industrial reuse applications, in tertiary treatment by municipal systems, and in concentration of brine. The long-term operation statistics show that ceramic nanocomposites have lower lifecycle costs, although their upfront cost is higher because the frequency of membrane replacement is reduced, less chemical cleaning is needed, and they are more stable (Sun *et al.*, 2024).

#### Challenges and Limitations of Ceramic Nanocomposite Membranes

Even though ceramic nanocomposite membranes are becoming accepted as strong, high-performance materials to use in the purification of water, they are still facing numerous unresolved problems that have hindered their large-scale use and long-term performance. Although these materials demonstrate excellent chemical stability, mechanical strength, and tunable surface properties compared to traditional polymeric membranes, the advantages are often compensated by challenges related to fouling behaviour, relative complexity of fabrication, cost, nanoparticle safety, long-term durability as well as regulatory compliance. These compounding problems should be overcome to bring laboratory-level achievements into reliable industrial and municipal water-treatment solutions.

Fouling of membranes is one of the most difficult operational problems facing ceramic nanocomposite membranes. Despite the natural resistance of ceramic substrates to fouling compared with polymeric membranes, the development of nanomaterials fails to fully stop the mechanisms of fouling. Even organic macromolecules, colloidal particles, microorganisms, and inorganic salts may settle on membrane surfaces or in the pores, causing the loss of flux, transmembrane pressure, and increased energy consumption during operation (Sutrisna *et al.*, 2024; Xu *et al.*, 2022). The addition of nanocomposites can also lead to additional

surface roughening with the possibility of making foulant adsorption more severe without careful control of surface chemistry. Many mitigation methods have been suggested, such as hydrophilic surface coating and the inclusion of antifouling or photocatalytic nanoparticles, which include TiO<sub>2</sub>, ZnO, and Ag, as well as optimisation of the microstructure to discourage fouling deposition (Moghimi *et al.*, 2025). Although such techniques mitigate temporary stability in flux and reversibility of fouling, they have seldom been used to offer long-term solutions. The physical backwashing and chemical cleaning is required on a regular basis, which adds operational complexity and leads to progressive wear and tear of material and increased lifecycle costs (Sutrisna *et al.*, 2024; Li *et al.*, 2020). Thus, creating membranes with intrinsically self-cleaning membranes or fouling-tolerant surfaces, exclusively as opposed to fouling-resistant finishes, is a fruitful but unmet area of research.

Another significant contentious feature to intensify deployment is fabrication cost and scalability. The development of high-performance ceramic nanocomposite membranes typically involves one of the energy-intensive steps and sintering at a high temperature, vacuum-assisted deposition, or multistep functionalisation of the surface, along with high-purity ceramic powders and nanomaterials (Kotobuki *et al.*, 2021). These demands are causing a rise in the costs of capital and operation of polymeric membranes, making it less competitive to provide where cost is a significant factor.

The costs connected with fabrication reduction have been the use of low-cost precursors (natural clays, fly ash, industrial by-products, etc.), low-temperature synthesis pathways, and simplified coating methods (Yuan *et al.*, 2025; Gu *et al.*, 2021). This notwithstanding, such solutions come with new problems of reproducibility, control of pore structure and homogeneous dispersion of nanomaterial at industrial scale. The changes in the composition of the raw materials and conditions of the processing might threaten mechanical integrity and the performance over time. At that, the scarcity of large-scale manufacturing infrastructure of ceramic membranes in comparison with polymer membrane structures also contributes to slow commercial uptake.

A specifically critical limitation is nanoparticle leaching and environmental safety-related issues. The presence of metal and metal-oxide or even carbon-based nanomaterials has the benefit of providing catalytic, antimicrobial, and adsorption-enhancing capabilities but increases their likelihood of nanoparticles entering the treated water streams (Ewis *et al.*, 2021; Kotobuki *et al.*, 2021). Leaching can be due to mechanical abrasion, extended chemical contact, or even the repeated process of regeneration and may bring toxic or reactive species to the environment.

In spite of surface functionalisation, covalent bonding, and polymer-mediated anchoring approaches as reducing nanoparticle release, their evaluation at long-term operating conditions is not fully demonstrated (Xu *et al.*, 2022). A significant number of studies assess leaching in laboratory conditions that are not representative of real wastewater, such as varying pH, salinity, and competing ions. This lack of standardized leaching procedures and thorough environmental analysis makes it harder to obtain regulatory approval and be accepted by the surrounding citizens. As a result, one of the paramount challenges is to design nanocomposite membranes, which will guarantee strong nanoparticle immobilisation without compromising the functionality of the membrane.

Long-lasting stability and regenerative behaviour also should be of key concern. Although most types of ceramic materials are usually tough and strong, nanocomposite systems provide interfaces which can be damaged during the course of time under mechanical, thermal, and chemical pressure (Li *et al.*, 2020; Xu *et al.*, 2022). Enhanced filtration and regeneration may cause microcracking, pore enlargement or weakening in nanomaterial/ceramic interfaces, which cause progressive permeability or selectivity. However, even though some studies claim that performance has stayed consistent during decades of operation, there is limited literature on long-term studies taking months or years (Sutrisna *et al.*, 2024). This is

because it has not been tested extensively in the field in order to be sure of the longevity and economic feasibility of the ceramic nanocomposite membranes. When discussing the viability of ceramic nanocomposite membranes, along with the technical factors, regulatory and lifecycle issues continue to take on an increased influence. Policymaking is changing to cover the emissions of nanoparticles and chemicals leaching and the disposal of advanced materials at the end of their lives (Xu *et al.*, 2022). It is not only the recycling or disposal of membranes that contain a metal or metal-oxide nanomaterial that are of concern to secondary pollution and occupational safety. According to the research on lifecycle assessment, ceramic membranes have the advantage of having a long service life and a low replacement rate, but their generation is more likely to consume more energy and produce carbon emissions than the production of polymeric membranes (Li *et al.*, 2020). Unless this initial investment in environmental costs is executed carefully by choosing the materials and optimising processes, the net gains on operational sustainability might only be counterproductive. Central lifecycle studies incorporating fabrication, operation, regeneration, and disposal periods are thus needed in the formulation of greener ceramic nanocomposite membrane technology.

### Future Perspectives and Research Directions for Ceramic Nanocomposite Membranes

It is true to say that ceramic nanocomposite membranes are being recognised as a foundation to next-generation water treatment technologies due to their excellent chemical resistance, mechanical integrity, and adjustable separation characteristics. Nevertheless, the progress of the framework from laboratory-sized demonstrations to large-scale industrial and municipal applications relies on the methodical solution of sustainability, scalability, functional adaptability, and regulatory acceptability. In this connexion, the further study should overgrow the improvements of performance and view the issue with a holistic notion of involvement of system-level integration, environmentally friendly production, and sustainable operation long-term.

Among the most promising areas of research, the design of green and sustainable strategies of fabrication should be mentioned. The traditional production of the ceramic membrane requires high purity of raw material and requires an energy-intensive production process, which contributes to environmental and economic costs to a great extent. More recent research has thus investigated the utilisation of natural minerals, bio-derived materials, industrial by-products, and ceramic wastes as alternative feed materials (Baig *et al.*, 2024; Dommati *et al.*, 2019; Li *et al.*, 2021). These materials have shown the capacity of minimising carbon footprints and material expenses and still maintain vital mechanical and separation properties. Nevertheless, to ensure reliable pore architecture as well as repeatable performance with feedstock composition remains a problem, requiring standard processing instructions and sound quality control models.

The methods of green synthesis also cover the synthesis of nanomaterials that are integrated into such ceramic materials. The use of solvent-free, aqueous, or low-toxicity synthesis methods of metal oxides and carbon-based nanomaterials is increasingly becoming popular as an approach to reducing the amount of risks posed to the environment and occupational health and safety by nanotechnology (Baig *et al.*, 2024). Though these methods are very beneficial in the context of sustainability and regulatory consideration, more research is needed to determine whether or not the green-synthesised nanomaterials have the same long-term stability, catalytic productivity, and interfacial bonding as the traditionally manufactured counterparts.

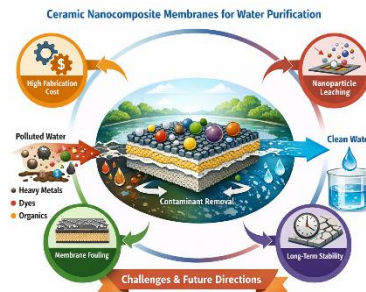
A new opportunity to the ceramic nanocomposite membrane is in digital manufacturing, especially additive manufacturing. The recent developments in ceramic slurry rheology, direct ink writing, and binder jetting can be used currently to produce very complex and hierarchical pore structures with greater precision than ever before (Ang *et al.*, 2024; Li *et al.*, 2021). Additive manufacturing is unlike conventional sintering or casting processes, in which the membrane structures are designed digitally, which optimises fluid flow,

reduces pressure drop and increases fouling resistance. Nevertheless, such an architecture has the drawbacks of scalability, speed of production, and cost-efficiency. This technology to make the most of itself will be heavily reliant on bridging the rift between the laboratory-scale 3D printing and the industrial throughput.

The other unbeatable frontier is the creation of intelligent and responsive ceramic nanocomposite membranes. Photocatalytic nanomaterials (TiO<sub>2</sub>, ZnO and g-C<sub>3</sub>N<sub>4</sub>) can be incorporated to allow in-situ destruction of organic foulants by light irradiation and thus prevent the use of chemicals to clean the membranes and increase their service life (Rasouli *et al.*, 2023; Baig *et al.*, 2024). Despite the promising prospects of these systems, their performance in practice under actual wastewater environments, where photocatalytic performance can be impaired by light penetration, turbidity and parallel reactions, is not well known.

Another avenue that can be used toward self-cleaning and adaptive operation is electroactive ceramic membranes. Preventing foulant adhesion with electrical stimuli or forming reactive species or heating a localised region can be used to clean several flux recovery without using chemical reagents or downtime (Ewis *et al.*, 2021). They are especially relevant to decentralised and continuous flow systems; however, it has to be borne in mind that their energy needs, stability of electrodes, and safety on a long-term basis are matters which demand a critical review.

In addition to the individual membrane functionality, hybrid treatment systems are anticipated to centre the focus of increasingly more complex water matrices. Ceramic nanocomposite membranes can be integrated with several complementary processes (ozonation, biological treatment, coagulation or advanced oxidation) to help improve contaminant removal and reduce fouling (Pendergast and Hoek, 2011; Rasouli *et al.*, 2023; Ewis *et al.*, 2021). These ranges of hybrid configurations have been shown to offer synergistic properties, especially when dealing with high-strength industrial wastewaters, but also add complexity to systems which require close optimisation of process sequence, energy usage and operational control.



### Img: Challenges and future perspectives of Porous Ceramic Nanocomposites

Although these technological advances have occurred, there are several empty knowledge gaps that need to be internationalised before the actual use of ceramic nanocomposite membranes can be implemented on any large scale. There is a paucity of long-term field validation; even in the response to realistic hydraulic, chemical, and mechanical loading, most studies are restricted to short-term laboratory experiments (Xu *et al.*, 2022; Ewis *et al.*, 2021). Long pilot-scale tests will be necessary to measure the durability, efficacy of regeneration, reversibility of fouling, and actual cost of life cycle.

The future of this field will be more determined by environmental and regulatory concerns. The leaching of nanoparticles, environmental effects, and occupational exposure need to be fully researched to meet the changing risk levels (Dommati *et al.*, 2019). In addition, the life-cycle assessment models should be extended in order to measure energy use, carbon footprint, and post-membrane disposal throughout the entire cycle of the membrane life cycle. Specifically designed regulatory guidelines that will be applied to ceramic nanocomposite membranes will play a significant role in accelerating the commercialisation process without making innovation irresponsible or unsustainable.

## Conclusion

Porous ceramic nanocomposites have emerged as one of the most promising materials concerning advanced water purification, with the merits of strong ceramic skeletons and the tunability and multifunctionality of nanomaterials. Their evolution portrays a lot of advancement in the enhancement of the membrane performance based on engineered porosity, escalation of the surface properties, as well as the resistance to chemical, thermal, and mechanical stress. The use of nanomaterials, including carbon nanotubes, graphene oxide, metal oxides, metal-organic frameworks, and inorganic-organic structures, has helped membranes to overcome most of the weaknesses of the traditional ceramic and polymeric systems. The improvements have seen them become more permeable and selective, having better antifouling characteristics and more stable operation over time, and this has placed ceramic nanocomposites at the top of innovative water treatment technologies.

Regardless of these achievements, recent trends in the field of research on ceramic nanocomposite membranes exhibit some areas of significant breakthroughs, as well as unresolved problems. Luckily, industrial applications have grown steadily on the positive side, particularly where resilience under extreme conditions is required. These are contaminated wastewater of high salinity, oil-water emulsions industrial effluents of high temperature and chemically aggressive surroundings, causing failure or quick degradation of polymeric membranes. Nanocompositions of ceramics are steady in flux, elevated solid rejection and lower cleaning rate than conventional alternatives. Their mechanical and chemical inertness qualities enable them to resist both operational stressors that would destroy other forms of membranes and become more appealing to long-term or continuous-use systems.

Nevertheless, there exist numerous technical and economic limitations to the widespread adoption. The cost of fabrication is also one of the major barriers. Conventional procedures are based on sintering processes that require a lot of energy and high purity of raw materials, which makes production more expensive. Although the application of low-cost or waste-based precursors has shown promising outcomes in lab research, the transfer of these approaches into the manufacturing of large-scale membranes without affecting their functionality is still a significant challenge. Also, it is technically difficult to sustain consistency in the dispersion of nanoparticles, the homogeneity of membranes, and the architecture of pores at larger scales.

The issue of the leaching of nanoparticles is another critical matter that needs to be paid attention to. Even though the bonding characteristics of most nanomaterials are high when they are incorporated in ceramic systems, over time exposure to environmental parameters such as different pH, ionic strength and mechanical forces, among other factors, may affect the leaching properties in real-life systems. Safety by way of standardised leaching tests, long-term stability tests and regulatory conformity will have to be completed before full-scale introduction into drinking water uses can be made. Although it is decreased as compared to the polymeric membranes, fouling is also an inevitable challenge. Regardless of engineered surface chemistry and nanomaterials integration, foulants may build up with time and cleaning, whether by chemical, thermal, or mechanical treatment, can bring about slow changes in the structure of the membrane.

In more detail, it is possible to see the future research directions towards sustainable fabrication, intelligent membrane design, and better connection with other forms of treatment technologies. Green synthesis methods such as utilisation of natural minerals, recycled ceramic materials and low temperature densification processes are on the increase, with scientists trying to minimise the negative effects on the environment and cut down on production costs. In the meantime, the digital manufacturing and additive processes are resulting in accurate regulation of the geometry, thickness and hierarchical arrangement of the pore, enabling membranes to be designed with a structural complexity that has never been available before. The above methods have a high potential of creating optimised-flux, minimised-fouling, and minimised-waste membranes.

Coexisting with these advances in fabrication are the development of smart ceramic nanocomposites that respond to stimuli. Environments may cause membranes to have self-cleaning or adaptive capabilities by incorporating photocatalytic, electroactive or thermoresponsive components. Indicatively, it is possible to use photocatalytic nanomaterials to eliminate the foulants on organic surfaces under the influence of light and to use electroactive systems to antagonise fouling by employing the controlled manipulation of surface charge. The features had the potential to greatly increase the life cycle, minimise the costs of maintenance, and enhance the sustainability of the procedures.

The other critical orientation is the synthesis of the ceramic nanocomposite membranes in the hybrid water treatment systems. An integrated approach of membrane filtration with an advanced oxidation process, biological treatment, adsorption media or catalytic reaction step enables several purification processes to synergise, to cover the progressively complex contaminant profiles of industrial wastewater and new emerging pollutants. The hybrid systems can minimise the fouling, increasing the efficiency with which the contaminants are removed, and improving the resilience in operations, and, thus, they can be used in centralised and decentralised water treatment facilities.

To make the most of the potential of the porous ceramic nanocomposites, though, several knowledge gaps will have to be solved. In comparison with the large amount of laboratory research, field-scale and pilot-scale demonstrations are now limited. Such long-term studies on operation are required to measure durability, energy usage, fouling behaviour, regeneration rate, and cost-performance ratios of operation under realistic applications. Also, lifecycle assessment, such as raw material extraction, fabrication, operation, cleaning and end of life disposal, will be essential in determining the actual sustainability and environmental footprint of these membranes. This kind of information will also be used to ensure that definite regulatory frameworks are developed to help in the safe use of nanomaterials in the treatment of water.

On balance, porous ceramic nanocomposites have the potential to revolutionise water purification technologies due to their stability, tunability, and multifunctional qualities. Further development of sustainable manufacturing, enhanced nanomaterial integration, and system-level innovation will enhance their competitiveness as well as their applicability. Porous ceramic nanocomposites, subject to strict field validation, critical policymaking, and strategic investment in scalable processes, stand a good chance of being able to cross into a phase of emerging research materials into a globally accepted solution to water purification problems.

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