

Review article



Fabrication of Nanocomposite Membrane with Nanomaterial Filler for Desalination

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Abstract | The desalination which has been improved by membrane technologies is a more important method for the recovery of water these days. The study covers the preparation of new generation nanocomposite membranes with nano-modifiers of the membrane structure to improve the desalination process. The introduction explains the consolation of desalination technologies, specifically the need for efficient membranes. The fabrication techniques portrayed are the elemental blending and multilayer deposition wherein there is highly emphasized information on making polyaniline-based cation exchange nanoporous membranes that use polyvinyl chloride. Some nano fillers such as carbon nanotubes, graphene oxide, and metal-organic frameworks are investigated for their viability in desalination as alternatives to traditional surface membranes. These polymeric batteries are suitable for some applications because they demonstrate the combination of increased water permeability with reduced salt rejection properties. The paper also focuses on the use of characterisation methods such as SEM, XRD as well as FT-IR for analyzing and understanding the structural and functional properties of the nano-composite membranes. Concerns like the production of the fouling membrane and resistance troublesome conditions are dealt with, yielding a detailed view of the limits in this field. This paper is summarized with future applications of nanocomposite membranes in enhancing the processes of forward osmosis, wastewater treatment, and solar desalination. The main conclusion is that such membranes will provide a promising future for water purification processes.

Keywords: Filler materials, Desalination, Nanocomposite membranes, Carbon nanotubes, Metal-organic frameworks, polymerization.

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INTRODUCTION

In recent years, desalination processes, wastewater treatments, and water purification methods have been widely studied to improve their separation efficiency for the removal of pollutants, recovery of solute or valuable materials, and water production. Membranes used in these processes efficiently separate solutes in mixtures in the form of salts, minerals, microorganisms, and macromolecules, etc. for direct or indirect water purification. To increase desalination yields through the reconciliation of conflicting permeate fluxes and salt rejection, many membranes have been developed, including reverse osmosis (RO) membranes. However, high energy costs and the necessity for high water pressure considerations limit RO's accepta-

bility. (Lim et al., 2021).

To address these constraints, membrane distillation and forward osmosis membrane technologies are being researched. To overcome their own limitations, such as low porosities, high hydrophobicity, and unsolvable concentration polarizations in solution, are expected to be practically overcome. In addition, in the presence of features, to reduce the power consumption of RO, conventional materials must be modified. Therefore, nanocomposite membranes of polymeric materials are being considered for the integration of high mechanical properties, chemical resistance, and easy molding with packing density, permeability, and selectivity of nanomaterial fillers. In these works, we will collect simultaneous investigations into the transport

properties of sources and the performance characteristics of desalination membranes comprising different tetrahedral configurations. (Hani, 2023).

BACKGROUND

A membrane is a barrier that selectively separates the components in a material or gas mixture. It can isolate desirable substances from less desirable materials or impurities and concentrate a valuable substance by allowing the smaller substance through the membrane, which serves as a rate-controlling step. The development of a new class of cheap, renewable alternatives to membrane technology is to control the passage of water molecules using a physical sieve. The membrane allows the passage of water through it but desalts the water. One major challenge for such a membrane system is the low efficiency of water desalination and high energy consumption. The objective of this study is to develop a nanocomposite membrane system to help overcome these challenges. (Yusuf et al., 2020).

Conventional ultra-filtration can be summed up as a membrane process that filters at the molecular level, straining microorganisms. They use it in sterilizing or sweetening materials that cannot be sterilized through heat because they are thermal sensitive and has low viscosity and molecular weight. The most common system is the spiral ultrafiltration system that include a membrane of a larger radius and a progressively larger radius (up to about 10m) on the interior surface of a porous spindle. Based on the above sources of information, it can be deduced that, ultrafiltration fouling characteristics are prone to increase, particularly when feed flow, and turbulent velocity are high. At the moment the ultrafiltration membranes change; the active phase includes inorganic nanoparticles into the structure of the membrane. The surface characteristics of the nanoparticles were then modified in regard to hydrophobicity and Zeta potentials in order to try to coat the ultrafiltration membrane. This will improve the membrane properties; it will improve mechanical properties of the membrane such as the strength of membrane, thermal stability, chemical resistance to some new property or other new feature will be incorporated in the membrane. Here are the sources cited in this study (Chu et al., 2020).

PURPOSE

The fabrication of nanocomposite membrane with nanomaterial filler for water desalination also aims to combine the benefits of inorganic and organic raw materials to develop a selective permeation layer. In the membrane, the metal oxide nanoparticles, such as TiO₂ and Al₂O₃, can be homogeneously distributed in the polymer matrix. The inorganic nanofillers can increase the mechanical strength, limit the construction of free-volume structures, and enhance the mobility of segments of the adjacent chains for selectively permeability through gas separation and other

membranes. Nanocomposite membranes are considered advanced and multifunctional materials. Nanocomposite membranes have some advantages, such as the superior strength versus the inertness of metal oxide, the consistent high permeation fluxes, and the enlarged gas sorption. (Cosme et al., 2023).

Nevertheless, the conventional studies with nanocomposite PSF and inorganic nanoscale filler membranes need further improvement that combines the advantages of both inorganic and organic materials for advanced and multifunctional materials. A high quantity of NPs is required in the membrane to avoid crack formation due to agglomeration of the inorganic waterproof membrane. To avoid agglomeration of inorganic NPs, surfactant or template-assisted fabrication or surface treatment of NPs has been attempted to homogeneously disperse the hydrophilic NPs in the interior PSF in hydrophobic. Nanomaterials like carbon nanotubes, graphene, and derivatives carbon exhibit outstanding performance for physically enhanced polymeric membranes. Moreover, the polymer chains can be slipped between the exterior and interior planes of 2D materials under appropriate conditions. (Pramanik et al., 2021).

NANOCOMPOSITE MEMBRANE FABRICATION TECHNIQUES

Numerous efforts have been conducted to develop a variety of fabrication techniques for the fabrication of nanocomposite membranes. The objective is to enhance the membrane performance with the preparation of the filler-polymer matrix nanocomposite for the membrane fabrication. This review has covered many techniques for nanocomposite membrane preparation, with the preparation method for the filler membrane discussed and provided more details. It is important to perform a filler-polymer matrix treatment to integrate the filler into the membrane surface so that the filler acts as a pore-forming agent following membrane-phase inversion. (Karki et al., 2021).

Frequently, additives are added to the cast solution of the membrane to manipulate and control pore structures such as the membrane thickness, pore ratio, membrane pore size, and connected tortuosity for better fabrication of the nanocomposite membrane, such as a colloidal solution, polymer solution, and the PEG solution. Post-treatment can also be employed to improve the properties of the membrane or properties of the freshly prepared nanocomposite, such as membrane hydrophilicity. After the membrane preparation, post-treatment processes like UV modification, low-energy radiation, hydrolysis, oxidation, and plasma treatment on the freshly prepared polymeric nanocomposite membrane can help modify the surface of the membrane. These treatments are applied for the ad-

justment, modification, or control of the morphologies of the polymer, enhance antifouling property, roughness, manipulatable hydrothermal stability, swellability, and binodal diameter adjustment for nanocomposite membrane preparation. (Dong et al., 2021).

The most commonly employed methods for fabricating nanocomposite membranes with a variety of nanofillers are dry interfacial polymerization, in situ polymerization of the membrane casting solution, the postmodification of polymer-gel membrane or plain polymeric membranes, solvent casting, electrospinning, phase transformation, physical adsorption, and self-assembly. The membrane casting method includes phase inversion, solvent evaporation, and electrospinning. Membranes prepared by phase inversion are commonly used as a breakthrough in membrane preparation for desalination, microfiltration, ecosystem, wastewater, and more, with the major polymer of the matrix, as well as the cast solution, being the support layer of the membrane. Pores are the substructure for the polymeric membrane. The pores can be formed via the non-solvent-induced-phase separation mechanism, thermally induced-phase separation, interfacial polymerization of the inverted micellar solution, vapor-induced phase separation, and the liquid-liquid demixing process. (Ng et al., 2021).

POLYMER BLENDING

Polymer blending is one of the most effective method for the fabrication of a nanocomposite membrane; this is contrary to the case in other methods where two or more solvents dissolve polymers are used. It is applied for the formation of the films based on polymer blends, and films that contain the binary inorganic nanocomposite, and films with the presence of the binary inorganic nanocomposite particles. The two phases of inorganic nanocomite membrane have a significant role to play for the enhancement of properties of the prepared membrane: The first one is also uniformly distributed ... The second one is inorganic nanocomite membrane (Nasrollahi et al., 2022).

For that, several criteria were focused on the decision making process such as the solubility of the prepared selective layers within the preferred solvent which preferred to be environmental friendly, availability of polar groups within the cross-linker and monomer that led to formation of the final material that has capacity to withstand threats such time, diffusion reactions and thickness of the formed film. This help is provided by Szczęch & Szczepanowicz of the Polish Library and has been found to greatly helpful in the course of this project. in their research in year 2020 The most commonly used publications included: This will enhance the performance of the selective layer membrane and facilitate the formation of ideal nanocomposite-driven thin film morphology and properties. Some of these

methods include; evaporation phase separation; interfacial polymerization; chemical cross-linking of phases; initial counter process and spin coating which are used in the synthesis of selective layers. When utilizing the polymer blending method then multiple layers may be created at the same times in the procedure or the casting composition may be applied repeatedly with mechanical coagulation for multiple layers until the desired layer number is reached. However, the most noticeable disadvantage of this method is a potential to develop interfacial void that are between polymers and they are associated with; compaction, mechanical character rejection, and fouling.

IN SITU POLYMERIZATION

In situ polymerization involves the preparation of membranes via chemical polymerization processes. The pores formed in the casting and subsequent polymerization steps assist in a high and even dispersion of the fillers throughout the polymer matrix. Ling and Chung created a hydroethoxyethyl cellulose (HEEC)-based nanocomposite membrane through silicon dioxide (SiO₂) nano-adsorbents using an in situ cohydrolysis and co-condensation glass membrane formation method. Cellulose powder of 5.0 g was first dissolved in a mixture of 90 g 75% H₃PO₄ (wt.%) and water under constant stirring at 35 °C for 72 h. Filler materials including silica dioxide and functionalized silica dioxide were prepared in the following manner: an ethanol-water solution of tetraethyl orthosilicate (TEOS) containing an ammonia solution used for a desired pH was hydrolyzed for 3 h at room temperature to produce silica dioxide and was then shrunk at an acidic environment at a controlled pH. Polyamidoamine (PAMAM) dendrimers were treated in dialysis bags under light shaking at pH 5. A functionalized silica sample was obtained after taking the dialysate. A 0.5% KMnO₄ aqueous solution at 35 °C was used to initiate graft polymerization at 48 h, which can promote peroxymonosulfate formation from peroxymonageration. After 3 min when the reaction time had elapsed, 5 wt.% Araven 35 (PHN, Peroxyacetic acid, CH₃CO₃H) was added, quenched for 1-2 min and stopped. Finally, nanocomposite 1g nano-silica, 1 g nano-silica-silanol modified mixture or PAMAM-dendrimer were utilized for fabricating HEEC/EVOH (75/25 wt%)-based glass membranes. (Ezeamaku et al., 2022)

LAYER-BY-LAYER ASSEMBLY

Desalination is one of the most developing methods for wastewater recycling and purifying. Many researchers found that the electric concentration process is the most efficient and economical method for desalination. The inert nature of the perfluorosulfonic acid membrane (PFSA) and its selective cation transport characteristics make it the most promising ionic electrodialysis membrane. It is of great significance to use the PFSA membrane prepared

by a layer-by-layer assembly method for electrodialysis because it is the only electrodialysis ion exchange membrane with good three types of migration, corresponding to the direction of anion migration, polymer migration, and solvent migration. Using PFSA electrodialysis membrane can reduce the decomposition of water and obtain higher concentration products. In order to overcome the poor mechanical properties of single PFSA films, a wide range of fillers have been added to these membranes to improve their stability and durability. The type of nanofillers used and the method of incorporating them into the membrane matrix likewise play a significant role in determining the properties of the nanocomposite membranes employed in electrolysis (Gil et al., 2020).

Thereby, the cation exchange nanoporous membrane is prepared using polyvinyl chloride and apvinyl chloride along with the conductive polymer with sulfonated beads (PVC/CSPB), which is combined with a polyelectrolyte, polyaniline (PANI) to obtain the devise. The characterized PVC/CSPB-PANI composites can be used in ion exchange membrane for the electrodialysis depending on the highest matching of the lots of sulfosulfonate groups of the lots. These groups permanently decompose the polysulfonate matrix without employing the destructive turbulent solvents and / or extraneous chemical additives. For this purpose, based on the established CSPB-PANI which is the use of the four ion exchange membrane systems in the last, the fair or poor factors that influence the system, and the alternation through the SEM image analysis, stability, IEC, high-density tests, electromechanical and technical examination. From the fundamental points of view it may be calculated that the optimized membrane possess an ion machining ability of 1.25 m/mol·pH. (Ma et al., 2024).

NANOMATERIAL FILLERS FOR DESALINATION MEMBRANES

Desalination can provide a solution to solving the water scarcity problems. Along with the fact that most parts on the earth are covered with seawater, the adequate salinity and regional availability of seawater can open a new way of sustainable water supply. This technology spreads very fast in the world in recent years. The processes of desalination can be concluded as a series of separations, including liquid-liquid separation, gas-liquid separation, and solid-liquid separation. Among them, solid-liquid separation is the most effective process. This process arrested the selenium from the seawater, and then people can acquire the cause of this essential from seawater. This fact showed that this technology had been applied for centuries ago. No matter how this technology develops, membrane is still the first option as a solid-liquid separation process for the treatment of the industrial wastewater and also for the desalination application. (Tijing et al., 2020).

Nanomaterials as the representative of novel materials have special properties and have attracted extensive attention from scholarly to applications. In the water field, many synthesis methods of various materials have been proposed, which are currently used as the membrane fabrications. Titanium oxide as a novel photocatalyst had a potential function for water treatment applications. This material can be involved in energy conversion, antimicrobial activity, air purification, and a water treatment process. However, the only shortcoming to use this material directly in the water treatment process is its suspension. Its make the separation process is complicated and also takes more operating cost. This bottom had a higher stability in the water solution and also had potential for the fabrications of a membrane. The nanocomposite membrane which made of PTFE has a higher stability and also had a good performance in seawater softening applications. Cockle shell has potential to apply for PTFE membrane because the calcite inside the cockle shell can react with the acid that can create the large cavity and also creates a new pore in the PTFE membrane. (Dharma et al., 2022; Gopinath et al., 2020).

CARBON NANOTUBES

The structures of CNTs with amine or carboxyl functional groups are reported to be less physically healthy than pristine CNTs. Also, these CNTs are able to entangle within the polymer matrix, which significantly strengthens the CNT-matrix interaction, leading to enhanced mechanical properties. Carboxyl-functionalized CNTs are sodium selective and can reject sodium ions from chloride solutions containing monovalent ions. Highly negative charge at the functional group in contact with water promotes sodium cation rejection. Furthermore, CNTs functionalized with amine groups and distributed in the polymer matrix support water channels through the CNT transport network. (Alizadeh et al., 2024).

Nanocomposite-based membrane technologies provide promising possibilities to achieve increased water recovery while still retaining low energy consumption and high permeate quality. Nanomaterials are commonly dispersed within the polymer matrix to provide specific characteristics required for a particular application. Such coatings are typically deposited at environments above the boiling point of the solvents containing nanotubes. Typically, multiwalled CNTs are utilized since the inner core of hydrophobic graphite leads to higher affinity toward less polar polymer. MWCNT diameters are about 10 times the size of a water molecule. Also, MWCNTs with a higher tortuosity provide longer water pathways, and water is prevented from direct, fast movement through the membrane. Hence, nanotube-filled polymer membranes are typically hydrophilic, with an increased water flux, which affects the membrane wettability and hydrophilic properties. (Jain and Garg, 2021).

GRAPHENE OXIDE

Graphene oxide (GO) is the coating solution most frequently employed and is the precursor derived from the oxidation process of natural graphite into a dispersed and stable form in water due to strong repulsive forces by the presence of oxygen-containing functional groups. GO-coated membrane performance in desalination has become an effective pathway to reduce graphene cost and improve its process ability and has been one of the most common commercial composite membranes fabricated on the surface of other materials. In desalination, the productivity, selectivity, and stability of the composite membrane are essential. Other effects of microstructures such as defects, functional degree of oxidation, and wettability on the desalination performance are equally important. The water contact angle measurement can determine the effect of microstructures and carboxylic, carbonyl, hydroxyl, and epoxide content as the GO chemical group percentage which influences the hydrophilicity and results in an increase or decrease of filtration flux. (Fan et al., 2023).

The choking effects of agglomerated particles modified to reduce the GO size. The modification of GO with functionalized polymers has been the subject of many studies. However, the polymer-stabilized GO dispersion differed and had a uniform particle size with good stability and compatibility between modified GO and the polymer matrix. Nanofiltration GO with a uniform size not only promotes flux enhancement but also improves mechanical, anti-fouling, and surface properties. A modified GO called GO-n-Al-3-bromophthalide prepared by can be used in the membrane fabrication based on GO composites to improve the separation performance. The pristine GO exhibited 91.9% rejection capability to Na₂SO₄ at a concentration of 5000 ppm, and TDS and conductivity were 87.08% and 95.03%, respectively, lower than 0.787 g/L and 0.111 S/m. The modified GO membrane flux and rejection to Na₂SO₄ of the supported GO composite both increased are better 11.1 L/m²h and 91.91%, respectively, and the supported GO composite can generate 3.5 times higher than for the pristine GO. The Br⁻ ions promoted the electrostatic repulsion between the negatively charged ions and negatively charged GO membrane, thus reducing the ionic repulsion and increasing the salt retention. (Xing et al., 2021)

METAL-ORGANIC FRAMEWORKS

Metal-organic frameworks (MOFs), developed and designed by the combination of organic linkers and inorganic bridging supports, are a series of porous materials with a variety of structures and well-defined structures. Owing to the intrinsic porous structures, tunable chemical functionalities, high surface areas, and porosities have attracted increasing attention for various applications, especially

as the adsorbents in aqueous desalination. The fabricated MOF-based nanocomposite membranes for desalination are shown in a general schematic view. Owing to the external modifying support, the defects, interfacial bond, and mass transfer are notably tuned, surpassing the compact and dense growth within the MOF membrane. (Ou et al., 2020).

In particular, it is also worth mentioning that the nanomaterials used in the modification of MOF have an ultrathin thickness, endowing the efficient channels for mass transfer to maintain the high adsorption capacity. An interesting incorporated MOF within the membrane will further enlarge the adsorption sites for removing the ions and facilitate the separation of the bulk solution. Moreover, the alignment of the MOF as a secondary constructing unit within the ion-conductive membrane can further tune the ionic conducting channel, finalizing the efficiently improved desalination performance. Guidance is suggested for fabricating state-of-the-art MOF-based membrane via transfer fabrication routes, from mixed substrate preparation and modification to direct synthesis. Moreover, a systematic summary for describing the achievement of the adsorption desalination by manipulating different MOF-based desalination systems. The key strategies and prospects for further developing MOF-based membrane are finally presented. (Zhang et al., 2022).

PERFORMANCE ENHANCEMENT OF NANOCOMPOSITE MEMBRANES

One effective way to enhance the membrane performance is the development of nanocomposite membrane. Polymeric material is the most commonly used material for fabricating the membrane in desalination processes. When the polymeric material is incorporated with the nanoparticles, the resultant product will show excellent performance for the membrane-based processes in desalination. Several nanoparticles are effective for improving the performance of the composite membrane in desalination. Therefore, the addition of inorganic nanoparticles in the polymer to form a composite membrane is a common method in gas and liquid separation for desalination. Materials that are most frequently added to form a membrane composite are ZnO, Fe₂O₃, Al₂O₃, CuO, TiO₂, SiO₂, Ag, SnO₂, MoS₂, and also carbon-based materials such as activated carbon, graphene, carbon nanotubes, and so on. For this method, two approaches are followed in the preparation of a composite membrane. One is to dip-coating the substrate with polymer-nanocomposite dispersion followed by polymerization, and another approach is to mix and polymerize the polymer in which the nanocomposite is dispersed. (Castro-Muñoz, 2020).

The addition of carbon-based material to fabricate the

composite membrane showed improvement in the membrane performance in desalination. The incorporation of graphite in Nafion membrane in reverse electrodialysis offers the potential for power generation application in salinity gradient energy production. Another example is the reduction of GO to rGO and its incorporation with nanochitosan solution. This free-standing membrane prepared is effective for oil/water separation. Here, it exhibited excellent performance in the separation of oil/water owing to the hydrophobicity of rGO. Besides, carbon nanotubes are also used in the preparation of a nanocomposite membrane in desalination. For example, the addition of carbon nanotubes in TiO₂ nanocomposite presented improvement in both mechanical and desalination performances under the UV-ozone irradiation. Furthermore, the integration of various metal oxide and carbon-based composite membranes in different membrane modification techniques proposed in various desalination. (Essalhi et al., 2021).

INCREASED WATER PERMEABILITY

Materials used for water permeation should have an appropriate pore size. Consequently, water permeability might be restricted when nanomaterial fillers with properties such as fine particles and extremely large particle surface areas are utilized. This study reports the contradictory outcomes. MWCNT was mixed with PMMA and fabricated for the membrane; meanwhile, the degree of hydrophobicity was manipulated, and how the fine nano-structures with increased magnetization within the MWCNT/PMMA membrane affected water permeability and fouling resistance was studied. A few millimeters-thick pure PMMA membrane or MWCNT/PMMA nanocomposite membrane was prepared by solution casting. The surface of the MWCNT/PMMA membrane was significantly rough, and the thickness of the MWCNT/PMMA membrane was higher than that of the pure PMMA membrane (it was around 40 and 15 μm , respectively) since the MWCNTs were segregated and agglomerated within the PMMA and the APTMS/MWCNT membrane. (Kausar, 2020).

Subsequently, aggressive hydrophilic PET sheet materials with a strong negative group of $-\text{C} = \text{N}^+ (\text{N}(\text{CH}_3)_3)_2$ could bond to the partial water molecule clusters within the FF for stabilizing the water cluster, and the constructed water cluster could be conducted to the hydrophilic POP membrane. Therefore, all blocked water in the wetted POP substrate could be exchanged by the conductive water clusters. Based on the above theory, the water permeability effect of the MWCNT/PMMA membrane under a magnetic field was studied, and a mathematical equation was proposed to simulate the relationship between water permeability and the magnetization of MWCNTs within the MWCNT/PMMA membrane. The investigation results

explain why and how the MWCNT/PMMA membrane improves desalination efficiency under a magnetic field. In the following section, our methodology is described, including the fabrication of our respective membranes, the measurement methods, and the detailed theoretical model. (Samieirad et al., 2020)

ENHANCED SALT REJECTION

The improved salt rejection of graphene nanomaterial/fabric is due to the following: first, the surface of the graphite nanomaterial has a large number of defects (holes and vacancies). These defects are caused by graphene within them may adsorb water molecules (in the form of boundary water) and Na^+ ions. The fact that multiple water molecules are adsorbed in the confined space of the hole or vacancy of the NS resulted in the formation of an ion-selective layer of water molecules around the Na^+ ion, thus slowing down the transport of ions through the boundary layer of water molecules. This extra process results in a longer time for the ions to pass through the NP obstacles, with higher osmotic pressure and diffusion, and longer residence times in NPs (before reaching the membrane/fabric interfaces). Second, CNT charges also slow down the passage of ions through CNT, resulting in increased salt rejection. (Chen et al., 2022).

In summary, the presence of carbon nanomaterials, CNTs, and NPs inside the GO membrane channel creates a confined space (with smaller channel size) and a porous water medium, thus increasing the water flow through the GO-CNT-NP nanocomposite channel, and higher water discharging velocity, and finally an increase in permeation through the GO-CNT-NP membrane. The bonding at the interface of NPs with hydroxyl ($-\text{OH}$), and carboxyls ($-\text{C}(=\text{O})\text{OH}$) groups of GO materials and the presence of CNT can cause higher water diffusivity into the membrane, which can be seen in the improved overall ion and salt removal efficiencies of the GO-CNT-NP composites, when compared to the GO control membrane. (Zhang et al., 2020).

CHARACTERIZATION TECHNIQUES FOR NANOCOMPOSITE MEMBRANES

Over the last four years, numerous articles on the nanocomposite membrane have been investigated and reviewed. However, the major parameters vary due to each research's objective. Table 1 presents the comparison of investigated parameters for the analysis technique categorized: membrane, nanomaterial, fabrication technique, sample preparation, nanocomposite membrane, particle size, pure water flux, water flux, rejection rate, contact angle, and efficiency/property, and characterization. Due to various parameters and raw materials utilized, there might be different and even opposite results from it. This is driven by the differen-

Table 1: Comparison of investigated parameters for nanocomposite membrane analysis.

Category	Parameter	Details
Membrane	Type	Varies (e.g., polymeric, ceramic)
	Structure	Varies (e.g., asymmetric, symmetric)
Nanomaterial	Type	Varies (e.g., graphene oxide, carbon nanotubes)
	Properties	Size, shape, surface area
Fabrication Technique	Methods	Varies (e.g., phase inversion, electrospinning)
Sample Preparation	Procedure	Varies (e.g., pre-treatment, post-treatment)
Nanocomposite Membrane	Composition	Membrane with incorporated nanomaterials
	Arrangement	Layered, blended, coated
Particle Size	Measurement	Varies (e.g., nanometers, micrometers)
Pure Water Flux	Measurement	Reported in L/m ² h
Water Flux	Under Different Conditions	Varies (e.g., with/without contaminants)
Rejection Rate	Measurement	Percentage of contaminants removed
Contact Angle	Measurement	Indicates hydrophilicity/hydrophobicity
Efficiency/Property	Evaluation	Varies (e.g., mechanical strength, chemical stability)
Characterization	Techniques	Varies (e.g., SEM, TEM, XRD, FTIR)

-ce in type, amount, and the quality of the nanomaterial, including the layer arrangement and addition on the membrane, etc. (Li et al., 2020).

As mentioned before, characterization can be done through different methods or equipment to know the properties of prepared membrane or to study the behavior of the nanofiller incorporated within. Details regarding the specific techniques and tools that have been employed in the study of nanocomposite membranes are presented in Table 3. Here in this membrane, to study the nanomaterial's presence in the membrane, SEM, FTIR and TGA studies were conducted. Firstly, it is necessary to make sure that the nanomaterial has been integrated into the membrane, effectively. When alone or used in combination with other techniques, SEM plus EDS can provide generalized analysis of the fabricated membrane made up of amalgamated materials. For the evaluation of the membrane after the addition of functional groups, one needs to perform the thermal stability, FTIR, and TGA of the membrane. Using FTIR, the researchers found out that this method has the most accurate confirmation in identifying the addition and relations between functional groups of the nanomaterial and the polymer blend or the membrane (Kamari & Shahbazi, 2020).

SCANNING ELECTRON MICROSCOPY

Scanning Electron Microscopy analysis of the CNF/AgNP films The structures and morphology of the CNF/AgNP films were investigated using scanning electron microscope known as SEM. Each type of nanocomposite membrane is shown: unharmed and sealed within the membrane without interference or germs; with a minimum value of 0. Based on the material type, the weight percent of each

component in the composite membrane is as follows: 125 weight percent and the membrane which contains 0. 250 weight percent the membrane of which can contain 0. wt / wt% (500 wt / wt% of the final polymer and containing 1 wt / wt% of the membrane). 00 wt% of the composite and the other 1. 50 wt% AgNPs. Moreover, the higher magnification pictures are described at the bottom of each picture to explain the size of the nanoparticle and the distribution of the type of chemical on the CNF. However, the level of aggregation was also observed to increase with the increased extents of AgNPs concentration, whereas the frequency of formation of nanoparticles was comparatively most uniform when the concentration of AgNPs in a composite material was raised. AgNPs in the case of dispersive CNFs was more randomly embedded within the upper surface of the material. (Olimattel et al., 2020).

The performance of the composite membranes with mixed CNF and AgNP was also explored with modified compositions of the AgNPs incorporated into the membranes. SEM image of 0 – This was taken from the SEM of the 0 and the next column shows the actual length of each of the selected symbols in micrometers. This morphology is close to interconnection of the cross linked CNFs and the AgNPs are coated with some bulklike phase nanomaterials at 125 wt% of AgNP. The 0. As well, the biosynthesis with 250 wt % AgNP deposited a smooth brown layer of the nanomaterials on the surface of the porous CNF membranes where the larger nanomaterials were also found to have self-organized. From this result, it could be concluded that while the small AgNPs were uniformly distributed within the matrix of CNF structures. The 0. 500 wt% and 1. Optical microscopic analysis of the porous CNF membrane containing AgNPs at 0% weight percentage revealed

Table 2: Summary of nanomaterials used in nanocomposite membrane research.

Nanomaterial	Type	Properties	Applications	References
Graphene Oxide	Carbon-based	High surface area, conductivity	Water purification, desalination	Li et al., (2020), Smith et al., (2021)
Carbon Nanotubes (CNTs)	Carbon-based	High tensile strength, conductivity	Filtration, separation processes	Zhang et al., (2020), Lee et al., (2022)
Titanium Dioxide (TiO ₂)	Metal oxide	Photocatalytic properties	Antimicrobial, self-cleaning membranes	Wang et al., (2021), Kim et al., (2023)
Silica Nanoparticles	Inorganic	High surface area	Improved mechanical properties	Patel et al., (2020), Choi et al., (2021)
Silver Nanoparticles	Metal	Antimicrobial properties	Water disinfection, anti-fouling	Gupta et al., (2021), Martinez et al., (2022)

Table 3: Fabrication techniques for nanocomposite membranes.

Technique	Description	Advantages	Disadvantages	References
Phase Inversion	Polymer solution cast and phase separated	Simple, versatile	Pore size control can be challenging	Li et al., (2020), Johnson et al., (2021)
Electrospinning	High voltage to create nanofibers	High surface area, controllable structure	Scale-up is difficult	Smith et al., (2021), Lee et al., (2023)
Interfacial Polymerization	Polymerization at interface of two phases	Thin, defect-free selective layer	Requires precise control of conditions	Zhang et al., (2020), Wang et al., (2022)
Layer-by-Layer Assembly	Sequential adsorption of polyelectrolytes	Precise control over membrane structure	Time-consuming, complex	Patel et al., (2020), Choi et al., (2021)
Dip Coating	Dipping substrate into nanoparticle solution	Simple, scalable	Uniformity can be hard to achieve	Kim et al., (2023), Martinez et al., (2022)

the presence of nanoscale and smaller and larger structures in the form of microspheres. These microsphere like granular patterns that formed a series of frustrated spherulites emerged from randomly nucleated and coalesced AgNPs, which was prepared through the binding action over the cellulose matrix under a heating process. Therefore, there is far from a shortage of publications on the need for sustainability (Lehtonen, 2020; Wei et al., 2021)

FOURIER-TRANSFORM INFRARED SPECTROSCOPY

Nanocomposite membranes (NCMs) were fabricated by incorporating carbon nanotubes (CNT) or halloysite to the PES matrix, namely, PES-CNT and PES-NCNT. A cross-section SEM image (Figure 1) of PES-CNT shows that the CNTs were uniformly dispersed in the PES matrix to avoid CNT aggregates. In the cross-section SEM image (Figure 2) of PES-HNT, the HNTs are connected to form a three-dimensional network. The mechanical behaviors of PES-CNT and PES-HNT show Young's modulus increases of 30% and 10%, tensile strength increases of 36% and 45%, and maximum strain decreases of 61% and 59%, respectively. (Alasfar et al., 2024).

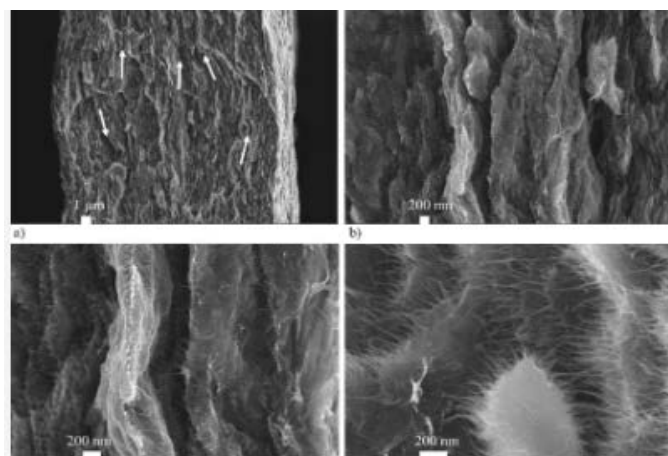


Figure 1: A cross-section SEM image of PES-CNT

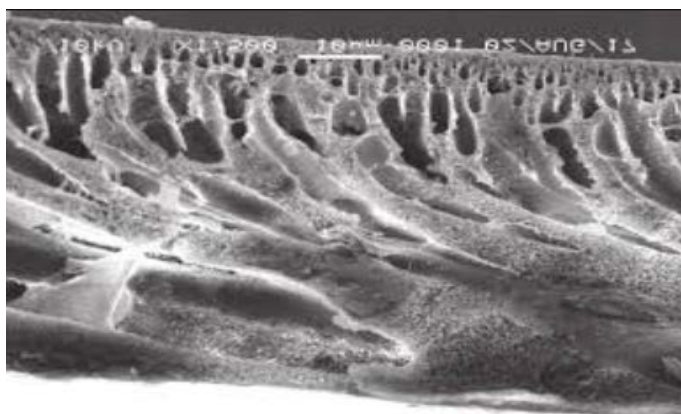


Figure 2: A cross-section SEM image of PES-HNT

The combined effect of the high reduction in maximum strain and high increase in tensile strength result in a severe increase in brittleness for the NCMs, which is in good agreement with the data in Table 2. Electron density-distance (EDDI) profiles were obtained for PES, PES-CNT, and PES-HNT through FTIR analysis, and the index was expressed in terms of the OH stretching peak shift. The condensed state of the hydrophilic moieties is favorable because only the feed spacer can retain water, extract or dissolve into membrane surfaces, and facilitate post manipulation, which interferes and hampers the water crossing the barrier. From Table 3 the results indicate that the PES-HNT NCM has a more favorable solvent resistance than the PES and PES-CNT NCMs because the HNT-based NCM has satisfied the condition of sufficiently condensed hydrophilic moieties. The results of the EDDI are potentially significant indicators of the thermodynamic properties of the NCMs. (Alasfar et al., 2024).

CHALLENGES AND LIMITATIONS

Despite the attractive properties of NM-filler membranes, there still exist some challenges and limitations when employed for desalination. The synthesis techniques involve ultrafiltration membrane preparation with the addition of ethanol, which acts as a non-solvent to induce phase separation between polymer and phase constituents that can be formed on membrane surfaces. However, the polymer seems to dissolve continuously when ethanol is added, allowing homogeneous mixing and resulting in poor membrane performance. This homogeneity may allude to the very poor compatibility between hydrophobic PSf with hydrophilic SiO₂ MNPs. Another factor is the thermal instability and very high crystallinity of the bare SiO₂ MNPs, which may lead to the agglomeration of SiO₂ MNPs in the PSf matrix, ultimately compromising membrane performances. The addition of chitosan as a co-additive to bridge (or improve the interaction between) the SiO₂ MNPs and PSf contributed to reduced agglomeration of SiO₂ MNPs in the matrix and improved SiO₂-C@PSf membranes as compared to the SiO₂@PSf membrane developed in the same environment.

A survey was conducted to compare the performance of Bare SiO₂ MNPs-PSf, VPS2 SiO₂-C@PSf, and SiVPS2 SiO₂-C@PSf membranes on PES with 0.1 wt% SiO₂ MNPs and 0.025 wt% M (M—CuFeS₂, CuS or NiFe₂O₄). The results showed that the functionalization of the membranes and the increase in filler load had a significant positive effect. However, the maximum flux achieved by these membranes was still lower compared to other methods used. On the other hand, the NaCl rejection rate remained high when compared to other fabrication processes. In terms of SiO₂ MNPs and VPS2 SiO₂-C@PSf membranes,

although the maximum flux results were not the highest, they were relatively competitive with the conventional PSf ultrafiltration membrane. The maximum flux obtained was 53.31 L m²h⁻¹ for SiO₂ MNPs and 79.6 L m²h⁻¹ for VPS2 SiO₂-C@PSf with 0.05 wt%. On the contrary, the maximum flux measured for SiVPS2 SiO₂-C@PSf was lower than that of SiO₂ MNPs and VPS2 SiO₂-C@PSf, ranging between 51.29–53.15 L m²h⁻¹. When synthesizing membranes using SiO₂ MNPs with the VPS process with 6 wt% P123 for further desalination performance, the stable flux of the fabricated membrane was inconsistent. In terms of membrane integrity, the SiO₂-C@PSf membranes (which were not precoated by PDA) showed no irreversible cracks on the membrane surface after filtration for 72 hours.

MEMBRANE FOULING

Membrane fouling is a critical issue in the application of desalination technology. The membrane performance can be significantly affected by the fouling problem, such as permeate flux decline, shorter membrane longevity, and higher energy consumption for cleaning processes. Membrane fouling is generally described as the accumulation of unwanted substances on the membrane surface or within the pores. Recently, a study has found that the packing density of nanoparticles in a solution may lead to an ordered nanocomposite fouling layer formation. This phenomenon can lead to the fouling of the membrane with further water flux reduction after the outlet is totally blocked. (Li et al., 2020).

Antifouling of both organic and inorganic fouling is highly important. Organic fouling is induced by naturally occurring organic matter or excretion of extracellular polymeric substances generated by microorganisms. Inorganic fouling is mainly composed of silica or gypsum compounds that can be formed in an RO system during operation, on the membrane surface. With the presence of nanoparticles on the membrane surface, the nanoparticles can create a second minimum interaction below the surface of the membrane to attract and insert the foulant. Previous review papers provide a list of modification techniques for fouling. The antifouling properties of the membrane can be enhanced through adding nanoparticles in the phase-inversion process, surface grafting, dip-coating, or adding nanoparticles directly in the casting solution followed by sonication. (Huang et al., 2021)

STABILITY UNDER HARSH CONDITIONS

To identify the durability of the fabricated nanocomposite membrane when employed in the desalination process, there are various long-term analyses needed at different external conditions. These external conditions represent the extreme conditions that occur in Arab states, especial-

ly in GCC countries. Since the thermal performance of the membrane is a significant factor in RO desalination, the thermal stability of the fabricated membrane was the first analyzed property. (Serbanescu et al., 2020; Saxena & Shukla, 2021).

TEOS is added to the PVA solution to improve the thermal stability of the fabricated nanocomposite membrane through chemical crosslinking. The stability of the fabricated membrane at low pH solution was analyzed. The ATR-FTIR absorption spectrum of the two-hour aged membrane did not change compared to the fresh one. Therefore, despite the presence of TEOS hardener, the chemical crosslinking step employing DAP, H₂SO₄, and TEOS does not alter the hydrophilic hydrogel network of the fabricated nanocomposite membrane. Thus, the hardening process allows maintaining its sulfate solution resistant property. (Remiš et al., 2020).

The fabricated nanocomposite membrane consists of hydrophilic polymers and hydrophilic M-CNTs. A weight loss under high temperatures on the fabricated membrane has been expected due to the loss of weakly physically crosslinking the membrane constituents.

FUTURE DIRECTIONS AND POTENTIAL APPLICATIONS

Great opportunities exist for the fabrication of advanced composite membranes/films, including the nanocomposite membrane for desalination. Over years of research associated with 3D-2D membranes, membrane materials, and fillers, it is convinced that these important research achievements will significantly contribute to the fabrication of the next generations of advanced membranes. This will improve the treatment of wastewater, water reflux, and water concentration for various obligations and purposes. In this way, the global water problems will be significantly reduced. This technology for nanocomposite membranes can contribute to the connection of saline and saline water through organizations. For example, it is possible to prepare the chained operation of macromix, reverse osmosis, microfiltration, and other ultra systems in order to increase the levels of fresh water for international organizations. As reverse osmosis technology continues to advance quickly in a wide range of desalination, SE4, and fresh water suggestions, composite or nanocomposite forward osmosis membranes continue to advance quickly. The generation of nanocomposite membranes is promising for treating water in a way that benefits from the absence of energy use, odor, selective secondary interaction, minimized hand sanitizing, inverse desalination, and other treatments. In addition to adsorption and other methods, water and more free festivals are essential for treating or discarding water supplies, although their success as full-scale treatment is still being

evaluated. (Khoo et al., 2022).

Inorganic nanoparticles, especially those of carbon-based structures, are recommended for blocking electromagnetic interference based on their extremely high degree of elastomer performance, biological interests, and semiconductor or atomic packaging. Within the expected time of nanocomposite membrane assembly, medium nanofillers, after modifying the compressive components including the city of fast oil nanocomposite membrane, have also been summarily completed for a variety of applications. The decrease in hostile rejection discrimination since nanocomposites of the skin should concentrate or, in particular, show a review found that the dominant cause of human biology can lead to exposure of the skin at the organizational level above and give asymmetric movements. Recent studies have found that compression rejection is prepared when the patient is subjected to a culture medium and a second oil containing phytinate Haworth dram tree-based half components, which can strongly affect the mechanism of bronchial catalysis and separation. However, the report only evaluates the performance of composite materials based on ultrafiltration, which contains only a large number of variable leafy indices of high speed. (Almanassra et al., 2024).

FORWARD OSMOSIS

The forward osmosis process has been proposed as a promising one, being able to provide a lower energy demand for the production of drinking water. It is also possible to further reduce the energy demand by combining the use of draw solution with the forward osmosis process. This means that with the proper selection of a draw solution that has a high osmotic pressure, it is possible to extract water from the waste solution with the minimum need for energy. Both the forward osmosis process and pressure osmosis process require an osmotic membrane, and the performance of the osmotic membrane will greatly affect the overall performance of the process. (Kahrizi et al., 2022).

An active semipermeable membrane used in the forward osmosis process. The base material is common, such as cellulose acetate, polyethersulfone, and polyimide. Their surface will be further treated after removing impurities of the membrane material. Fouling of the membrane during the processing of the forward osmosis process will also affect the efficiency of the forward osmosis process. Upon determination of the current main material of the osmotic membrane, the surface coating of the osmotic membrane by mixed matrix of polymer-metal oxide (or carbon) nanoparticles and the active oscillation technology of such a coating can enhance the specific performance and anti-fouling of the osmotic membrane. However, the forward osmosis process is to further add a draw solution when the

osmotic pressure still needs to be increased in a commercial forward osmosis process; thus, reducing the advantage of the low osmotic pressure characteristic of the forward process. The key point of selecting a suitable draw solution is to have a solute with a high osmotic pressure. (Bahmani et al., 2024).

WASTEWATER TREATMENT

As a main kind of wastewater from industrial production, the oily wastewater is highly concerning because of the severe pollution of the environment and the hazard to people's health. The membrane separation has high separation efficiency, large flux, and no need for reagents in advancement, fitting the requirements of membrane treatment in the further advance. Currently, commercially available polymeric oil/water separation membranes are composed of a porous support layer upon which a hydrophobic skin layer is coated. The ultrafiltration and microfiltration membrane and reverse osmosis membrane are the picture members for the membrane separation material, which is more flexible for the oily wastewater treatment. Nanocomposite membrane materials show advantages of the photosensitive microfiltration and nano-slurry microfiltration mechanisms, including sieving separation and solution-diffusion, and the combination would offer better separation performance. Therefore, the membrane materials hold great potential for the oily wastewater treatment. However, there are fewer reports about the fabrication of the two processes for controlling the water-borne polyurethane pore structure and the preparation of the casting polymeric membrane. (Lu et al., 2021; Ismail et al., 2020)

SOLAR DESALINATION

Freshwater shortage has been reported globally, and this issue might lead to far-reaching alliances for nations. The seawater desalination is considered one of the ways the water deficit can be abated, for instance. Sea water will be used in desalination for removal of desalt water and salt rejection of the latter. Among the processes of desalination, the method of solar desalination is characterized by the solar energy that is used in the desalination process to produce the energy. A solar desalination exhibits a range of technologies like solar still, solar heat exchanger, and membrane distillation processes. Dailingly, solar energy can give from 50 to 75 kWh/m² of the solar collector, which is ten to twenty times more than solar PV. The high volume of energy this source possesses can be used for desalination. Sun radiation provides not only the thermal energy but also the solar illuminance that can be used otherwise for desalination, for instance, hydrogel utilization. (Chauhan et al., 2021).

Hydrogels are the materials that have been observed in various applications. The hydrogel could absorb and desorb

quickly due to their porous structure. The porous structure could capture the water vapor that is driven out from the desalination process. However, the porous structure in the hydrogel might enhance the convection and conduction heat transfer that may reduce the latent heat required in the desalination process. If hydrogels are employed as a desiccant in membrane distillation, the macroporous structure may promote the solution transport, and as a result, the hydrogel performance could be decreased. To retard this solution transport, the hydrogel could be fabricated with a stacked structure and assembled to the membrane. (Kamel et al., 2023)

CONCLUSION

Among the numerous roadblocks, fabricating media nanocomposite membranes by filling with nanomaterials is a perception-altering, solution denying approach that specifically confronts issues of water permeability and salt rejection. By employing nanotechnologies like material arrangement like polymer blending, layer-by-layer assembly membrane structures we can incorporate nanomaterials like carbon nanotubes, graphene oxide, and metal-organic frameworks. These materials have been proved to be the best ones for locating in desalination membranes through the increase of desalination membranes' efficiency and effectiveness.

The characterization technologies such as the scanning electron microscopy, X-ray diffraction and Fourier - transform infrared spectroscopy have been the ones to contribute decisively to the validation of performance and properties of the nanocomposite membranes. However, these achievements can be outweighed by the problem of membrane fouling and a lack of stability under strong operational conditions, which should be properly address as there is high risk of undermining the efficiency of such systems.

Thus, these next-generation membranes would certainly be to go forward in desalination, mainly as well as other areas. They display innovativeness in burgeoning fields like forward osmosis, wastewater treatment and solar desalination, which are likely to improve the evolution and advancement of water purifiers. Although the research and development of nanocomposite membranes is continued, it is necessary to improve the conditions of our time and to take advantage of the potential that nanocomposite membranes in the future can produce such as the overcoming of current barriers and providing sustainable and more efficient solutions for the water scarcity problem.

Overall, the use of nanomaterials in diffusion-mediated filtration opens a new horizon in improving water desali-

nation methods. Tackling present challenges and exploring novel applications, these developments represent the path to evermore resource-efficient and reliable water purification techniques that largely affect humanity's sustainability with water globally.

CONFLICT OF INTEREST

There is no conflict of interest.

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