ISSN 2393-9850
GEM — Georgian Educational Mine
Interdisciplinary International Peer-Reviewed Research Journal
St. George's College Aruvithura, Kerala, India

Volume 3, Issue 1, 2023
Pages 63–68
gem.sgcaruvithura.ac.in

ORIGINAL RESEARCH ARTICLE

Role of Carbon-Based Sustainable Nanomaterials in Advanced Filtration Systems

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Received: 17 October 2023 · **Revised:** 22 November 2023 · **Accepted:** 13 December 2023 · **Published:** 18 December 2023

Keywords: Carbon nanomaterials; Membrane filtration; Carbon nanotubes; Fullerene; Graphene

Abstract

Nanomaterials are revolutionizing filtration systems with their unique properties, such as high surface area, tunable porosity, and enhanced chemical reactivity. Polymeric nanocomposite membranes embedded with nanofillers have demonstrated remarkable advancements over conventional membranes, including superior pollutant removal efficiency, enhanced water permeability, and improved resistance to fouling. The performance of these advanced membranes is heavily influenced by the type and concentration of nanofillers used. However, excessive nanofillers may lead to aggregation, diminishing their effectiveness. Despite their potential, challenges such as high production costs, environmental concerns, and the unintended release of nanomaterials during usage remain critical issues. Among these materials, carbon-based nanomaterials, such as fullerenes, graphene, and carbon nanotubes, are increasingly favored for wastewater treatment due to their exceptional adsorption properties and ability to significantly enhance membrane filtration for contaminant removal.

1. INTRODUCTION

The growing global population is driving an increasing demand for water, which in turn intensifies water pollution issues. Ensuring the protection of existing water resources and the production of clean drinking water through advanced technologies has become critically important. Membrane-based techniques have gained widespread acceptance as effective solutions for producing safe drinking water. These methods are both cost-effective and environmentally friendly, as they require minimal energy input and do not generate harmful by-products during the filtration process [Thomas et al., 2017, Bolisetty et al., 2019]. Membrane technologies are highly versatile, allowing for the selective removal of various contaminants by modifying pore sizes and surface properties [Qadir et al., 2017]. These techniques are categorized based on the driving force and separation mechanisms involved. Pressure-driven membrane processes, in particular, play a significant role in water purification. They can be broadly classified into microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), depending on the pore size and operating pressure requirements. Microfiltration and ultrafiltration are low-pressure techniques primarily used to remove suspended solids, bacteria, viruses, fungi, and macromolecules. These methods are ideal for preliminary water treatment and provide an effective barrier against larger contaminants [Cassano et al., 2018]. On the other hand, nanofiltration and reverse osmosis are high-pressure techniques designed for more advanced applications. These include the removal of small ions, organic pollutants, water hardness, and desalination. These processes are particularly useful for addressing critical challenges such as brackish water treatment and seawater desalination, offering reliable solutions for regions with limited freshwater resources [Jegathambal et al., 2019]. Polymeric membranes, widely used in water treatment, are cost-effective with tunable pore sizes but are more prone to fouling due to their hydrophobic nature, reducing filtration efficiency [Warsinger et al., 2016]. Additionally, they can degrade when exposed to chlorine, a common disinfectant.

Ultrafiltration membrane technology is extensively used for advanced wastewater treatment. However, its broader application is limited by issues such as poor hydrophilicity, low anti-fouling and anti-compaction properties, high costs, non-recyclability, and lack of selective adsorption [Padaki et al., 2015]. Among these, membrane fouling is the most critical challenge, caused by organic and inorganic deposits on the surface and within the membrane pores. This fouling, which can be reversible or irreversible, reduces permeate flux and shortens the membrane's lifespan, making its mitigation a key research focus [Bai et al., 2013].

Membrane performance can be enhanced by modifying surface functional properties, often through the incorporation of nanoparticles. These nanoparticles, with their unique properties and large surface area, significantly improve the characteristics of polymeric membranes [Jeevanandam et al., 2018]. Thus, the properties of polymeric membranes can be enhanced by the introduction of nanoparticles. Different types of nanocomposites, such as mixed matrix, thin-film nanocomposites, and surface-located nanocomposites, can be synthesized depending on the location and structure of the nanoparticles on the membrane. Carbon nanomaterials (CNMs) are highly sought after for membrane technologies because of their distinctive structural properties. This review discusses various carbon-based nanocomposite membranes and their efficiency in improving the filtration properties of polymeric membranes.

2. SURFACE FUNCTIONALIZATION OF MEMBRANE SYSTEMS WITH CARBON-BASED NANOMATERIALS

Nanotechnology has advanced significantly and is widely applied in water and wastewater treatment. Traditional methods like extraction, oxidation, and adsorption, though effective, are often expensive. Nanotechnology offers a cost-effective alternative for detecting and removing pollutants from wastewater [Nishu and Kumar, 2023]. Carbon nanomaterials are extensively utilized in advanced membrane materials for wastewater treatment. Their size-dependent properties make them highly effective in removing organic and inorganic contaminants [Sheoran et al., 2022]. They have gained significant interest in scientific research and the textile industry for water purification due to their exceptional contaminant removal capabilities and unique features [Gusain et al., 2020]. These materials offer distinct advantages over traditional water purification systems [Smith and Rodrigues, 2015]. Their high surface area enables superior adsorption, while properties such as high reactivity, fast dissolution, superparamagnetism, and quantum confinement enhance their effectiveness [Tiwari et al., 2024]. Based on carbon atom arrangements, carbon nanomaterials can be classified into various types, including carbon nanotubes (CNTs), graphene, and fullerenes [Georgakilas et al., 2015]. Despite differences in surface morphology, they are effective in removing organic contaminants, pathogens, and heavy metal ions, which can pose serious health risks [Smith and Rodrigues, 2015].

2.1 Carbon Nanotubes (CNTs) Based Nanoparticles

Carbon nanotubes (CNTs), composed of rolled graphene sheets, are widely used to improve membrane performance. Both single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) enhance functionality by enabling near-frictionless water transport, creating high-flux, highly permeable membranes [Das et al., 2014]. Incorporating CNTs into polyethersulfone membranes improves antifouling properties, particularly during protein filtration (e.g., albumin and ovalbumin) under cross-flow conditions [Celik et al., 2011]. This enhancement minimizes fouling, boosting membrane efficiency and durability, making them more suitable for high-performance filtration applications. The increased hydrophilicity of the membrane also reduces protein adsorption on its surface. It has been reported that the presence of MWCNTs in polyamide reverse osmosis membranes increases chlorine resistance due to the presence of carboxylate groups [Zhao et al., 2014]. Tijing et al. developed superhydrophobic nanofiber membranes with MWCNTs, achieving enhanced performance. The MWCNTs increased permeability, improved porosity, and enhanced mechanical strength based on their loading. These membranes showed a permeability of 24–29.5 $\mathrm{L\,m^{-2}\,h^{-1}}$, outperforming commercial PVDF membranes with 18–18.5 $\mathrm{L\,m^{-2}\,h^{-1}}$ [Tijing et al., 2016]. Agglomeration of CNTs raises surface roughness, but this can be mitigated by introducing functional groups such as carboxyl, polyethylene glycol, or amine [Bai et al., 2015].

2.2 Graphene-Based Nanoparticles

Graphene is a two-dimensional sheet of sp^2-hybridized carbon atoms arranged in a honeycomb lattice, exhibiting exceptional electrical, molecular sieving, and mechanical properties [Smith et al., 2019]. Nonporous graphene and graphene oxide (GO) have been developed for modern membrane separation applications due to their molecular sieving capabilities. GO sheets used as nanofillers in polymer membranes promote polymer chain alignment, creating smoother surfaces [Zhu et al., 2018]. Chemical oxidation of graphene produces GO, introducing hydroxyl ($-OH$) and carboxyl ($-COOH$) functional groups. Its high porosity and surface area make it highly effective for wastewater treatment. Its compatibility with polymers enhances mechanical strength and hydrophilicity, primarily driven by the $-OH$ groups in its structure [Chadha et al., 2022]. Graphene–polyurethane composite membranes were developed for water and gas desulfurization within a polyurethane matrix. With 0.8% graphene content, the membranes achieved an optimal enrichment factor of 4.32 and a permeability flux of 1411 $\mathrm{g\,m^{-2}\,h^{-1}}$ [Peng et al., 2022]. For water–oil separation, membranes with superhydrophobicity and superoleophilicity were created, and the addition of graphene oxide improved separation efficiency to 99% [Rasouli et al., 2021]. GO, intercalated with oxygen-rich functional groups, serves as an effective nanocomposite material with excellent dispersion in polymer matrices [Cheng et al., 2017]. Polyamide membranes functionalized with GO nanosheets demonstrated notable antimicrobial properties [Perreault et al., 2014]. After one hour, the functionalized membrane inhibited the growth of 65% of bacteria. The performance of GO can be further optimized through various functionalization methods. A polyethersulfone membrane coated with polyethylenimine-modified GO exhibited improved biocompatibility, along with excellent antifouling and antimicrobial properties [Yu et al., 2013]. In another study, positively charged amine-containing GO and negatively charged GO were alternately deposited onto a polyethersulfone membrane via layer-by-layer assembly. The resulting nanocomposite membrane was stabilized by electrostatic interactions and hydrogen bonding, exhibiting a 53.8% reduction in surface roughness, which significantly improves fouling resistance [Choi et al., 2013].

Amide membranes are commonly used in water purification; however, the widely used disinfectant chlorine degrades the membrane material due to the formation of N–Cl bonds during chlorination. By incorporating GO, the chlorine resistance of the polyamide membrane was improved, along with enhanced NaCl rejection. The electron-rich GO acts as a protective shield for the inner polyamide layers against chlorine attack [Song et al., 2016]. Additionally, the GO layer restricts the passage of reactive chlorine species (e.g., OCl^-) via size exclusion [Choi et al., 2013]. Charge repulsion between the reactive species and GO further contributes to this rejection mechanism [Hu et al., 2017]. Combining CNTs with GO improves their dispersion within polymeric systems. Since GO exhibits surfactant-like properties, it interacts with CNTs through non-covalent interactions, enhancing their dispersion in aqueous solutions [Akhavan et al., 2011]. Furthermore, a 5:5 mixture of CNT and GO coated on polyvinylidene fluoride (PVDF) ultrafiltration membranes exhibits superior fouling resistance compared to membranes containing either CNT or GO alone [Zhang et al., 2013]. One of the critical challenges in utilizing GO membranes for practical applications is the marked reduction in water flux over time [Kang et al., 2024]. Addressing this issue is essential to ensure their long-term efficiency and viability in membrane operations.

2.3 Fullerene-Based Nanomaterials

Fullerenes are hollow, symmetrical carbon nano-allotropes featuring sp^2 hybridization and π-conjugation, with C_{60} (buckminsterfullerene) being the most extensively studied form [Radford et al., 2022]. This molecule is widely investigated for its optical, electronic, mechanical, thermal, and biomedical properties. High-performance fullerene-based nanocomposite membranes have been developed, with performance heavily influenced by the type of fullerene, its dispersion state, and its interactions with the polymer matrix [Djordjevic et al., 2015]. Fullerene-based reverse osmosis membranes have demonstrated high water flux ($26.1\ \mathrm{L\,m^{-2}\,h^{-1}}$) alongside excellent salt rejection [Perera et al., 2018]. Mixed-matrix pervaporation membranes were fabricated using polyamide–polyphenylene isophthalamide filled with fullerene nanoparticles and other carbonaceous fillers via solid-phase synthesis [Dmitrenko et al., 2019]. C_{60} grafted with polyvinylpyrrolidone (PVP) exhibits strong antibacterial properties, making it highly effective for wastewater disinfection. Surface modification of membranes with fullerenes improves flux recovery in protein-rich wastewater, effectively mitigating membrane fouling. Embedding 10% C_{60} into polyphenylene isophthalamide (C_{60}-PA) enhances viscosity, density, water flux, and protein resistance compared to standard PA membranes [Penkova et al., 2009]. Fullerenes are incorporated into polymer membranes to form nanocomposites, which enhance the host polymer's mechanical properties and adsorption capacity. Excess Cu(II) ions in wastewater can be efficiently removed using fullerene-modified systems, demonstrating superior efficiency compared to standard nanocomposite polystyrene films [Dmitrenko et al., 2019]. The addition of nanofillers enhances transport properties, as validated by testing with an azeotropic methanol–toluene mixture. Fullerene molecules strengthen matrix–nanofiller interactions, improving nanostructure compatibility. However, achieving uniform nanoparticle dispersion within polymeric membranes remains a significant challenge [Vladisavljević, 2024].

3. CONCLUSIONS

The incorporation of nanoparticles significantly enhances the performance of polymeric membranes. Carbon nanomaterials hold immense promise for wastewater treatment due to their exceptional optical, electronic, and catalytic properties, combined with their large surface area and nanoscale features. Their performance depends on the type, size, shape, and composition of the nanomaterials, as well as the polymer support utilized. The integration of suitable nanomaterials improves the antifouling characteristics, chlorine resistance, and overall stability of membrane systems. However, long-term stability under operational conditions remains uncertain. Scaling up production processes and further optimizing mechanical properties and durability will be crucial to expanding their applications across diverse environmental and industrial fields.

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