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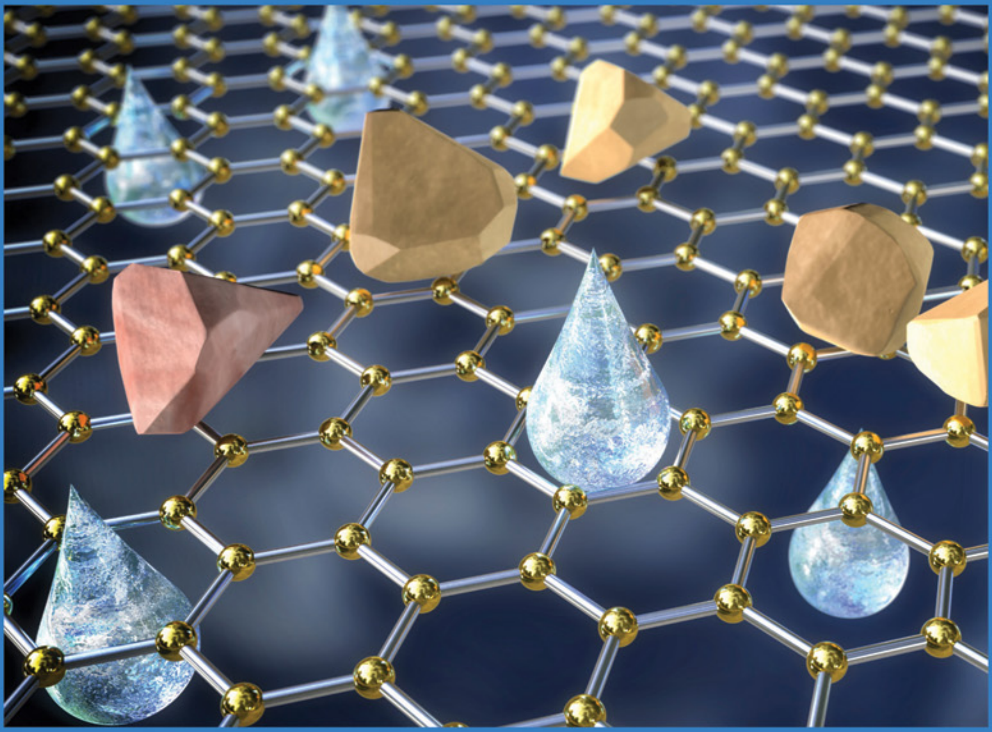

POLYMER NANOCOMPOSITE MEMBRANES IN WATER TREATMENT AND DESALINATION

RECENT DEVELOPMENTS, FUTURE OPPORTUNITIES, AND SUSTAINABLE APPLICATIONS

Edited by
MD. REZAUR RAHMAN
MUHAMMAD KHUSAIRY BIN BAKRI

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Polymer Nanocomposite Membranes in Water Treatment and Desalination

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Woodhead Publishing is an imprint of Elsevier
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
125 London Wall, London EC2Y 5AS, United Kingdom

ISBN: 978-0-443-23879-6 (print)
ISBN: 978-0-443-23880-2 (online)

For information on all Woodhead Publishing publications
visit our website at https://www.elsevier.com/books-and-journals

Publisher: Matthew Deans
Acquisitions Editor: Gwen Jones
Editorial Project Manager: John Leonard
Production Project Manager: Kamesh R.
Cover Designer: Gopalakrishnan Venkatraman

Typeset by MPS Limited, Chennai, India

Dedication

This work is dedicated to my amazing wife and daughters; Shirin Akther, Fahriah Rahman, and Faizah Rahman, who are very special to me and made it possible for me to complete this work.

—Ts. Dr. Md. Rezaur Rahman

First, I would like to thank the Almighty God for the guidance, strength, power of mind, protection, and for giving us a healthy life. All of these we offer to you. Every difficult task needs self-effort as well as the guidance of elders, particularly, those who are near to our hearts. I offer my humble dedications to my beautiful and loving father, mother, wife, and brothers, whose devotion, love, support, and nightly prayers have enabled me to work toward this significant achievement, along with all the dedicated, well-liked, and well-respected teachers and supervisors.

—Ts. Dr. Hj. Muhammad Khusairy Bin Bakri

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Preface

Water scarcity is one of the most pressing global challenges of the 21st century, with a growing demand for clean, safe, and accessible water resources. As the world's population continues to rise and industrial activities expand, the need for efficient water treatment technologies becomes more urgent. Among the various approaches to addressing this challenge, membrane filtration technologies, particularly those involving polymer nanocomposite membranes, have gained significant attention in recent years. These membranes have shown exceptional promise in a wide range of applications, from desalination and wastewater treatment to oil removal and heavy metal filtration.

This book provides a comprehensive exploration of the latest advancements and future opportunities in this critical area of research. Polymer nanocomposite membranes, which combine the structural advantages of polymers with the unique properties of nanomaterials, have emerged as a highly effective solution for water treatment. The incorporation of nanoparticles into polymer matrices enhances the performance of traditional membranes, improving their permeability, selectivity, and durability. These enhancements make them ideal candidates for various separation processes, such as reverse osmosis, desalination, and the removal of organic contaminants, heavy metals, and bacteria.

In the opening chapters, we introduce the recent developments in polymer nanocomposite membranes, highlighting their versatility and effectiveness in water treatment applications. The subsequent chapters delve into specific applications, including reverse osmosis, desalination, oil removal, dye and pesticide removal, and the treatment of water contaminated with bacteria and heavy metals. These applications are explored with a focus on the mechanisms that govern their performance, as well as the latest research that continues to push the boundaries of what is possible with these materials.

One of the significant advantages of polymer nanocomposite membranes is their ability to address complex and diverse water contamination issues simultaneously. For example, membranes used for oil/water emulsion separation not only provide high filtration efficiency but also exhibit strong resistance to fouling and degradation, which are common challenges in conventional filtration methods. Additionally, the unique photocatalytic properties of some polymer nanocomposite membranes enable them to break down organic contaminants in water, further expanding their potential in water purification technologies.

Throughout the book, we emphasized the importance of interdisciplinary collaboration in advancing the field of polymer nanocomposite membranes. The synthesis and application of these materials require expertise from diverse fields, including chemistry, materials science, engineering, and environmental science. As we continue to develop novel membrane technologies, the need for sustainable, cost-effective, and scalable solutions will drive innovation, paving the way for more efficient water treatment processes that can meet the demands of a rapidly changing world.

This book aims to serve as both an educational resource and a reference for researchers, engineers, and policymakers working in the fields of water treatment, desalination, and environmental protection. We hope to inspire further research and development in this exciting area, contributing to the global effort to ensure access to clean water for all.

We extend our gratitude to the contributors who have shared their expertise and insights in this volume. Their dedication and innovative approaches are shaping the future of polymer nanocomposite membranes, and we look forward to the continued advancements in this field.

Ts. Dr. Md. Rezaur Rahman
Ts. Dr. Hj. Muhammad Khusairy Bin Capt. Hj. Bakri

Introduction to recent developments and future opportunities for polymer nanocomposite membranes

1

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1.1 An overview of nanocomposites

The process of urbanization and industrialization has resulted in a rapid increase in the usage of water (Cheng et al., 2023), hence worsening the worldwide water problems. Water pollution has a significant impact on several parts of the biosphere, such as humans, the atmosphere, aquatic habitats, and other connected organisms. This impact results in considerable expenses (Abdali et al., 2017). Contaminants from diverse sources, such as household trash and industry operations, including paper making, agriculture, and textile production, continuously degrade water quality. Although there have been significant gains, it is still crucial for the world to make coordinated efforts to ensure that everyone has access to safe and clean water (Hazarika et al., 2023).

As per studies from the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), around 844 million people globally do not have sufficient access to safe drinking water (WHO/UNICEF, 2017). Furthermore, according to United Nations research, approximately 1.2 billion people worldwide are experiencing a lack of available water, while an additional 0.5 billion are very close to facing the same conditions. Additionally, around 2 billion people are facing financial limitations when it comes to accessing water (Bassyouni et al., 2019). The undeniable importance of clean water for survival is unfortunately overshadowed by the fact that only a small fraction, little over 1%, passes the international requirements for cleanliness (Gude, 2017).

The intensification of industrialization has worsened a notable environmental issue related to the cancer-causing and extremely poisonous characteristics of heavy metals (HMs) present in water sources. These noxious substances tend to build up in the human body, resulting in harmful consequences such as harm to organs, impairment of

Polymer Nanocomposite Membranes in Water Treatment and Desalination. DOI: https://doi.org/10.1016/B978-0-443-23879-6.00001-4

the nervous system, and delayed growth and development (Bolisetty et al. 2019). Prolonged ingestion of water contaminated with these hazardous metals, as emphasized by the World Health Organization (WHO), can lead to serious ailments affecting crucial organs such as the lungs, kidneys, skin, and bladder (Jehan et al., 2020). Zinc (Zn), mercury (Hg), cadmium (Cd), selenium (Se), nickel (Ni), lead (Pb), and copper (Cu) are frequently found as hazardous metals in industrial effluent and drinking water (Lim and Aris, 2014). These metals originate from either natural sources, such as rock weathering and volcanic eruptions, or human activity, primarily associated with industrial processes, including textile production, electroplating, fertilizer manufacturing, food processing, and painting. Various methods have been suggested to tackle this urgent problem, such as coprecipitation, electrochemical deposition, ion exchange, adsorption, flotation, crystallization, and membrane filtering. The combination of different treatment methods has been found to increase the effectiveness of removing metals from water. Out of these options, adsorption is particularly notable since it is economically viable, operationally simple, environmentally compatible, applicable over a wide pH range, and there are plenty of suitable materials available. Various adsorbents, such as clay minerals, zeolites, activated carbon, fly ash, polymers, and biochar, have been extensively studied for their ability to remove toxic metals from water. However, these adsorbents often present difficulties in terms of by-product generation and processing complexities (Srivastav et al., 2020). Recently, the field of nanotechnology has shown potential in several scientific areas, particularly in the use of different nanomaterials as adsorbents for removing hazardous metals from water. Nanomaterials possess remarkable attributes like a large surface area, improved adsorption sites, evenly dispersed pore diameters, and extended intraparticle diffusion lengths, consequently surpassing the performance of traditional materials (Borji et al., 2020). Various nano-adsorbents, such as carbon nanotubes, graphene, and metal oxide–based nanoparticles, have been studied for their ability to eliminate hazardous metals (Tyagi et al., 2017). Although nanosized adsorbents have a significant adsorption capacity, they face hurdles due to their inclination to aggregate into bigger particles because of van der Waals interactions and their high colloidal stability in aqueous solutions. In addition, nano-adsorbent powders have a low level of mechanical strength and a high-pressure drop, making it challenging and economically impractical to recover them after the adsorption process (Hua et al., 2012).

To tackle the difficulties linked to nano-adsorbents, it is necessary to include nanomaterials in a porous substrate, like a polymeric membrane. This approach shows great potential. This method involves incorporating possible nano-adsorbents into the suitable matrix, resulting in a nanocomposite membrane that possesses both adsorption and membrane filtration capacities (Damiri et al., 2022). Membranes are classified according to the size of their pores into microfiltration (MF), nanofiltration (NF), ultrafiltration (UF), and reverse osmosis (RO). Additionally, they can be categorized based on their composition as either inorganic or polymeric membranes. Although there are options for inorganic membrane materials, including ceramics, amorphous silica, and metals, they are often expensive and have limited ability to adjust the distribution of pore sizes. As a result, their usefulness in water treatment is restricted (Ng et al., 2013).

Polymeric membranes, such as cellulose acetate, polyacrylonitrile (PAN), polyamide (PA), polycarbonate (PC), polyethersulfone (PES), polyethylene (PE), polysulfone (PSU), polyvinylidene fluoride (PVDF), polyvinyl chloride (PVC), polypropylene (PP), and chitosan, can adjust their pore size distribution, are cost-effective to produce, and exhibit exceptional chemical, thermal, and mechanical stability (Wen et al., 2019). The features of the materials can be customized by modifying additives, concentrations of monomers, and the conditions in which they are cast (Abdi et al., 2017). Nevertheless, polymeric membranes are susceptible to fouling as a result of their hydrophobic characteristics.

The addition of nanoparticles to the polymer matrix improves the elimination of harmful metal ions and reduces the problems caused by the buildup of unwanted substances on polymeric membranes (Pichardo-Romero et al., 2020). Different manufacturing techniques, such as phase inversion, interfacial polymerization, electrospinning, physical deposition, chemical grafting, and layer-by-layer (LBL) assembly, have been used to get the desired properties of nanocomposite membranes (Nasir et al., 2019). While the potential of incorporating nano-adsorbents into polymeric membranes for the efficient removal of heavy metals from water is promising, there is a lack of comprehensive literature reviews on the progress and current concepts regarding nanocomposite membranes and their role in separating heavy metals from water.

Loeb and Sourirajan made a groundbreaking contribution to membrane technology in 1963 by creating cellulose acetate membranes with high flux rates, which were a major achievement in the field (Loeb & Sourirajan, 1963). The introduction of polysulfone and polyvinylidene fluoride (PVDF) membranes followed later advancements. In the 1970s, Cadotte pioneered the use of polyamide thin film composite membranes by employing interfacial polymerization (IP) to improve membrane rejection and flux rate efficiency. In the following years, the attention shifted towards improving the qualities of the membrane by modifying its surface by utilizing chemicals. Additionally, during the period from 2010 to 2015, a noteworthy achievement occurred with the development of membranes using hybrid and nanotube materials. This marked the beginning of the nanotechnology age.

Nanocomposite membranes are used to efficiently remove heavy metals from water, employing several processes to attain this goal. Recent research (Damiri et al., 2022; Memisoglu et al., 2023; Zhang et al., 2018, 2020) has clarified that these mechanisms include adsorption, chelation, size exclusion, electrostatic contact, complexation, and redox reactions. The adaptability and effectiveness of nanocomposite membranes in purifying water contaminated with heavy metals are highlighted by this multidimensional approach. It provides a comprehensive framework for understanding the membranes' ability to separate these elements.

Recently, there have been several significant review papers published in the same academic field. Damiri et al. (Damiri et al., 2022) conducted a thorough examination that specifically concentrated on the latest developments in nanocomposite membranes designed to adsorb heavy metal ions from contaminated water sources. Simultaneously, Harby et al. (2022) explored the capacity of polymeric nanocomposite membranes for water purification. In the field of water treatment, Cheng et al. (2023) provided valuable

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Over the past few years, significant research has been conducted into the development of polymeric nanocomposite membranes to increase environmental sustainability and to demonstrate their benefits for commercial water treatment and desalination applications. ***Polymer Nanocomposite Membranes in Water Treatment and Desalination: Recent Developments, Future Opportunities, and Sustainable Applications*** presents the latest research findings in this important field. This book summarizes current advances in the production, characterization, and applications of these membranes for water treatment and desalination. Bio-composite alterations, functional group additions, and nanomaterial assemblies are also examined in depth. The current breakthroughs in reverse osmosis, oil removal, heavy metals removal, dye removal, photocatalytic degradation of organic contaminants, and pesticide removal from wastewater are also discussed. Additionally, this book also highlights bacteria removal by polymeric nanocomposite membranes as well as the major benefits and drawbacks of various adsorbent materials. Special emphasis is also placed on the adsorption mechanism, which includes chemisorption and physisorption. This book will be a valuable reference source for academic and industrial researchers, as well as early career researchers who are working in the research and development of polymer nanocomposite membranes for water treatment and desalination.

Key Features

- Covers production, characterization, and applications of polymeric membranes for water treatment and desalination
- Discusses fundamentals, materials and methods, chemistry, synthesis procedures, and membrane preparation methods
- Methods of scaling up production from lab to industry are also covered in detail
- Focus on sustainability

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ISBN 978-0-443-23879-6

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