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Review article

Water Treatment Using Nanofiltration Technology: A Sustainable Way Towards Contaminant Removal from Wastewater

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ABSTRACT

Safe sources of natural water are becoming contaminated due to human activities such as industrialization, colonization and municipal wastes as the major sources. Various pollutants contaminate both surface and underground water reservoirs, posing significant hazards to ecosystems and human health. This article presents an overview of diverse sources of contaminants and their detrimental impacts on the environment and its inhabitants. Of particular concern are dyes, recognized as among the most perilous water pollutants due to their easily identifiable presence even without sophisticated detection technologies. Among the array of available techniques, adsorption emerges as one of the most suitable approaches for the removal of dyes from contaminated water. Consequently, the exploration of various adsorbents for dye removal is of paramount importance in safeguarding water quality and ecological integrity. This paper presents an overview of sustainable ways for removing contaminants from wastewater using nanofiltration technology.

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1. Introduction

Water is the essence for life. It is an indispensable resource that is critical for sustaining ecosystems, supporting human needs, and fueling economic activities. Responsible management of water resources, coupled with effective wastewater treatment, is pivotal to maintaining environmental integrity and public health (Kant 2012). Nanofiltration technology (NFT) has emerged as a highly promising and versatile separation technique for the production of drinking water from a wide range of water sources (Yusuf and Madhu 2022). These scenarios include surface water treatment, groundwater treatment, water reuse, brackish water treatment, and point-of-use applications. The achievements in removing major target pollutants such as hardness, pathogens, and natural organic matter underscore the importance of removing micropollutants of major concern, including disinfection byproducts, per- and polyfluoroalkyl substances and many more (Abbasizadeh et al., 2014; Guo et al., 2022; Fu et al., 2011). Contaminated water bodies pose severe risks, not only in terms of the ecological balance but also due to the transmission of waterborne diseases. In this context, the treatment of wastewater plays a pivotal role, ensuring that the water returned to nature or supplied to communities is free from harmful pollutants and pathogens. Traditional methods of wastewater treatment have often been associated with significant energy consumption, chemical usage, and waste generation. As the global population continues to grow and industrial activities expand, the need for innovative, sustainable technologies to treat wastewater becomes increasingly imperative (Jin et al., 2020; Kim et al., 2017). Nanofiltration technology has emerged as a promising solution in this regard. Nanofiltration, a membrane-based separation process, allows for the selective removal of contaminants from water while conserving valuable resources, making it a sustainable and environmentally friendly approach to wastewater treatment (Khan and Malik 2018). This review paper provides an overview of the significant progress made in NF-based drinking water treatment.

2. Background

Wastewater generated from various sources, including domestic, industrial, and agricultural activities, contains a diverse array of contaminants that pose substantial risks to the environment and public health. These contaminants encompass organic and inorganic pollutants, heavy metals, pathogens, nutrients, and emerging substances. When discharged into natural water bodies without adequate treatment, these

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pollutants can disrupt ecosystems, contaminate drinking water sources, and give rise to detrimental health consequences, for example, high levels of organic pollutants can deplete oxygen in aquatic ecosystems, causing fish kills, and the presence of pathogens can lead to the spread of waterborne diseases, making wastewater treatment a critical necessity (Khan and Malik 2018; Laraib et al., 2020).

Historically, wastewater treatment has relied on conventional methods such as sedimentation, coagulation, flocculation, and disinfection to eliminate contaminants from water. While these methods have proven effective to a certain extent, they often necessitate the use of large quantities of chemicals, substantial energy input, and substantial infrastructure. Coagulation and flocculation, for instance, require the addition of chemicals to promote the aggregation of impurities, while disinfection methods like chlorination can produce harmful byproducts. Additionally, these traditional approaches may struggle to effectively remove certain classes of contaminants, such as dissolved ions and small organic molecules (Loganathan et al., 2023). This work emphasizes the need for a fit-for-purpose design tailored to specific applications, aiming to enhance the separation capabilities of NF membranes for target compounds alongside their salt removal efficiency. Furthermore, the review highlights key considerations related to membrane fouling control, chlorine resistance, membrane integrity, and selectivity, providing valuable insights for the future development of high-efficiency NF membranes. Nanofiltration is an advanced membrane-based separation technology that operates on the principles of size exclusion and charge interactions. It employs semi-permeable membranes with pore sizes typically in the nanometer range, allowing it to selectively remove specific substances from water (Maryam et al., 2020; Moreira et al., 2022). This selectivity is based on the size and charge of the particles, ions, or molecules in the water. Larger contaminants are hindered from passing through the membrane, while smaller, uncharged molecules can permeate. The technology leverages both size exclusion and electrostatic forces to achieve separation, making it highly versatile for a wide range of applications in water treatment.

3. Sustainable Aspects of Nanofiltration

3.1 Environmental Benefits

- *Reduced Chemical Usage:* One of the foremost environmental benefits of nanofiltration technology is the significant reduction in chemical usage. Unlike traditional water treatment methods that often rely on the addition of coagulants, flocculants, and disinfectants, nanofiltration operates primarily through size exclusion and electrostatic interactions. As a result, the need for large quantities of chemicals is substantially diminished. This reduction not only lowers the environmental impact of chemical production and disposal but also minimizes the risk of harmful byproducts, such as disinfection byproducts (Maryam et al., 2020; Yusuf 2019; Sarkar et al., 2020), entering the environment. Nanofiltration offers several key advantages, which have contributed to its popularity as a sustainable water treatment solution:
- *Lower Energy Consumption:* Nanofiltration is inherently energy-efficient compared to processes like reverse osmosis. The lower energy requirements are attributable to the fact that nanofiltration membranes allow the passage of a broader range of particles than their more restrictive counterparts in reverse osmosis. This efficiency leads to reduced energy consumption during water treatment operations, contributing to a lower carbon footprint and reduced reliance on fossil fuels.
- *Minimal Waste Generation:* The design of nanofiltration systems facilitates the concentration and recovery of valuable components from the concentrate stream, often referred to as brine. This concentration minimizes waste generation and, in some cases, allows for the reclamation of valuable resources from the wastewater, such as valuable minerals or organic compounds. This sustainable approach reduces the overall environmental burden and disposal costs associated with wastewater treatment.

3.2 Economic Aspects

- *Cost-Effectiveness:* The sustainability of nanofiltration is closely tied to its cost-effectiveness. By reducing the need for chemicals and consuming less energy compared to traditional methods, nanofiltration can offer economic benefits to water treatment facilities and municipalities. Lower operational costs make nanofiltration an attractive option for areas seeking to improve their wastewater treatment infrastructure without exorbitant expenditure.
- *Long-Term usage:* In addition to the immediate cost-effectiveness, nanofiltration can result in long-term savings. Its ability to extend the lifespan of equipment, reduce maintenance requirements, and decrease the costs associated with disposing of waste and hazardous chemicals can translate into substantial savings over the years. This makes it a sound investment that aligns with long-term economic sustainability.

3.3 Social Aspects

- *Improved Access to Clean Water:* Nanofiltration has the potential to enhance access to clean and safe drinking water, especially in areas facing water scarcity or struggling with contamination issues. By efficiently removing contaminants, including pathogens and pollutants, nanofiltration can improve the quality of water supplied to communities. This accessibility to safe drinking water is essential for public health and has a profound impact on the well-being of communities.
- *Health Benefits for Communities:* As a direct consequence of providing cleaner water, nanofiltration contributes to the health and well-being of communities. The removal of pathogens and harmful chemicals from water sources helps reduce the incidence of waterborne diseases, safeguarding public health and decreasing healthcare costs. The social implications of nanofiltration extend to both urban and rural areas, where clean water is vital for daily life and agricultural practices.

Nanofiltration technology, with its environmental, economic, and social advantages, stands as a sustainable and multifaceted approach to water treatment, addressing critical challenges while promoting a healthier, more sustainable future.

4. Effectiveness of Nanofiltration in Removing Different Contaminants

Nanofiltration has demonstrated notable effectiveness in the removal of heavy metals from water sources. The technology's semi-permeable membranes can selectively capture ions and particles, making it particularly well-suited for this purpose. For instance, a study published by Kim et al. (2017) and Jin et al. (2020) investigated the removal of heavy metals, including lead and cadmium, by a nanofiltration system. The results indicated removal efficiencies exceeding 90%, highlighting nanofiltration's potential in treating water contaminated with heavy metals. Nanofiltration is also highly efficient in removing a wide range of organic pollutants, such as pesticides, pharmaceuticals, and volatile organic compounds. In another subsequent study, it was reported that the removal of various organic micropollutants using nanofiltration (Yusuf 2018; Teh et al., 2016; Qasem et al., 2021; Wuana and Okieimen 2011). The study found removal efficiencies of over 90% for many of the organic compounds tested, underlining the technology's efficacy in addressing this class of contaminants.

The proliferation of heavy metals in wastewater is a dire consequence of industrial expansion and human activities across sectors such as plating, battery manufacturing, mining, textile production, and petrochemical refining. These industries release a variety of heavy metals, including lead, mercury, chromium, and cadmium, into water bodies through processes like electroplating, mining runoff, and chemical manufacturing (Walha et al., 2007). This contamination poses significant threats to human health and ecosystem integrity, as heavy metals are non-biodegradable and can accumulate in the environment, potentially leading to carcinogenic effects and disrupting aquatic and terrestrial ecosystems. Addressing the pervasive issue of heavy metal contamination in wastewater demands a comprehensive approach involving regulatory measures, technological innovations, and public awareness campaigns. Strict effluent standards must be enforced to limit heavy metal discharge, while advancements in wastewater treatment technologies offer promising solutions for removal and remediation. Concurrently, fostering public awareness about the risks associated with heavy metal pollution and the importance of responsible water management is crucial for promoting sustainable practices and safeguarding water resources for present and future generations.

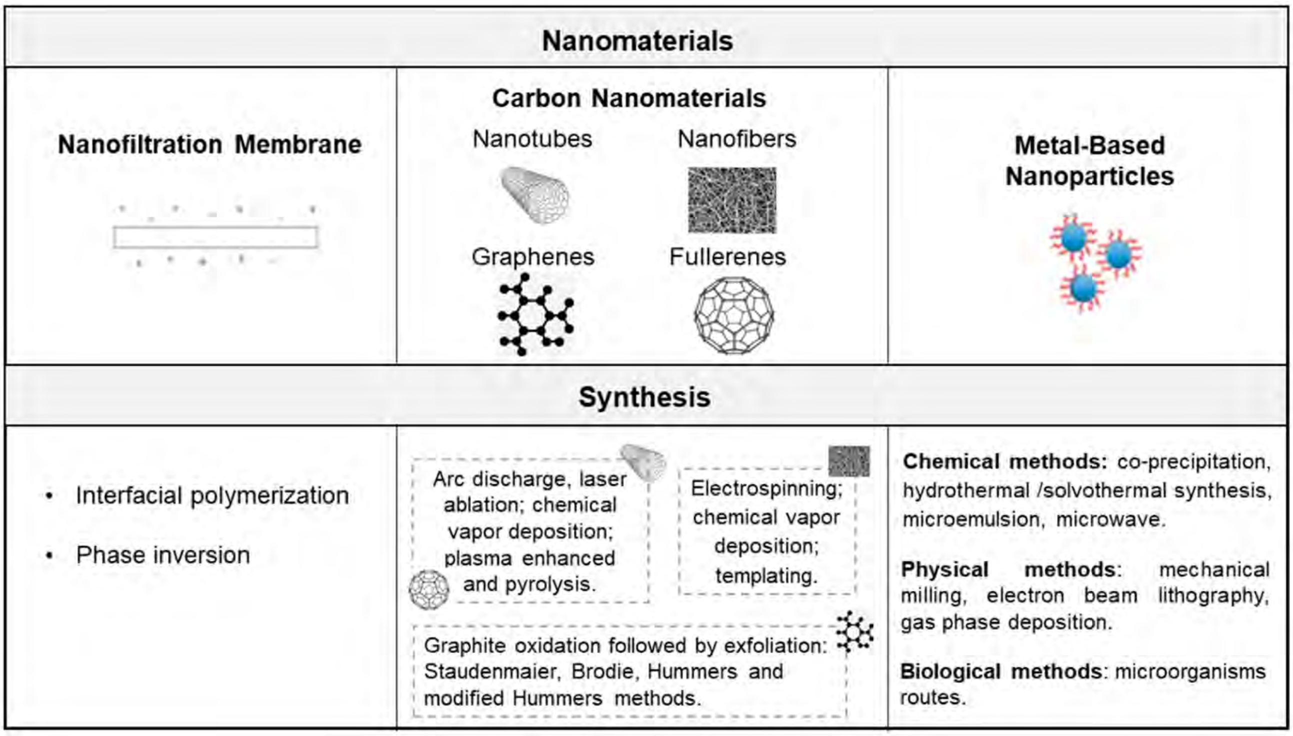

Figure 2. Schematic illustration of the synthesis of nanomaterials for application in the remediation of emerging pollutants (Adapted from Moreira et al. under CCBY MDPI 2022).

Additionally, nanofiltration process is capable of removing microorganisms, including bacteria and viruses, from water. Loganathan et al. (2023) recently investigated the removal of bacteria by nanofiltration membranes. The results indicated that nanofiltration was successful in achieving high removal rates, surpassing 99% for most bacteria, which is crucial for providing safe drinking water. Nanofiltration has shown promise in addressing evolving contaminants, such as endocrine-disrupting compounds and pharmaceutical residues. Furthermore, the removal of pharmaceuticals from wastewater using nanofiltration has been noticed as emerging alternative to the conventional ones, for example, removal of paracetamol, diclofenac and ibuprofen from wastewater by nanofiltration membranes (Yang et al., 2018; Yusuf, 2021). The study reported substantial removal efficiencies, marking nanofiltration as a viable solution for emerging contaminant removal. When compared to reverse osmosis, nanofiltration offers advantages in terms of energy efficiency (Yusuf, 2018). Reverse osmosis, while highly effective in removing contaminants, often requires higher operating pressures and energy consumption. In addition, a study was conducted a comparative analysis of nanofiltration and reverse osmosis for brackish water treatment and found that nanofiltration required significantly lower energy inputs while achieving comparable removal rates for various contaminants (Maryam et al., 2020; Moreira et al., 2022). Activated carbon filtration is proficient in adsorbing organic compounds but may require periodic replacement of the carbon medium. Nanofiltration, on the other hand, can achieve similar or better removal rates for organic pollutants without the need for periodic media replacement, making it a more sustainable and cost-effective solution. Traditional coagulation and flocculation methods can be effective for the removal of certain contaminants, but they often rely on the addition of chemicals and generate significant amounts of sludge.

Nanofiltration minimizes chemical usage and produces less waste. A similar study has been reported that describes comparative the performance of coagulation-flocculation and nanofiltration in the removal of heavy metals (Yusuf, 2019; Maryam et al., 2020; Moreira et al., 2022). The results favoured nanofiltration for its efficiency and reduced environmental impact. Nanofiltration stands out as a versatile and sustainable water treatment technology, offering effective removal of various contaminants while presenting advantages in terms of energy efficiency and environmental impact when compared to alternative methods. The adsorption process is intricately governed by a combination of factors including the physicochemical attributes of both the adsorbent material and the heavy metals present, as well as the operational parameters such as temperature, adsorbent dosage, pH level, adsorption duration, and the initial concentration of metal ions in the solution. This multifaceted interplay shapes the efficiency and effectiveness of the adsorption mechanism. Typically, heavy metal ions are attracted to and bound onto the surface of the adsorbent material, forming a crucial step in the removal process, as illustrated in Fig. 3a. This phenomenon underscores the importance of understanding the intricate dynamics involved in the adsorption process for optimizing treatment strategies in wastewater management and environmental remediation endeavors.

Carbon-based nanoporous adsorbents, such as activated carbons (ACs), carbon nanotubes (CNTs), and graphene (GN), are indispensable for heavy metal removal due to their extensive surface area (ranging from 500 to 1500 m^2/g). By introducing surface functional groups like carboxyl, phenyl, and lactone groups, these materials enhance heavy metal uptake efficiency and selectivity. ACs offer abundant active sites, CNTs provide a favorable environment for adsorption, and GN exhibits remarkable properties owing to its two-dimensional structure. Surface functionalization augments adsorption by facilitating specific interactions with heavy metal ions, such as coordination bonds and π-π interactions (Fig. 3b), thereby improving overall adsorption capacity and selectivity. This tailored approach holds promise for developing efficient and selective adsorbents to address heavy metal contamination in water sources and industrial effluents.

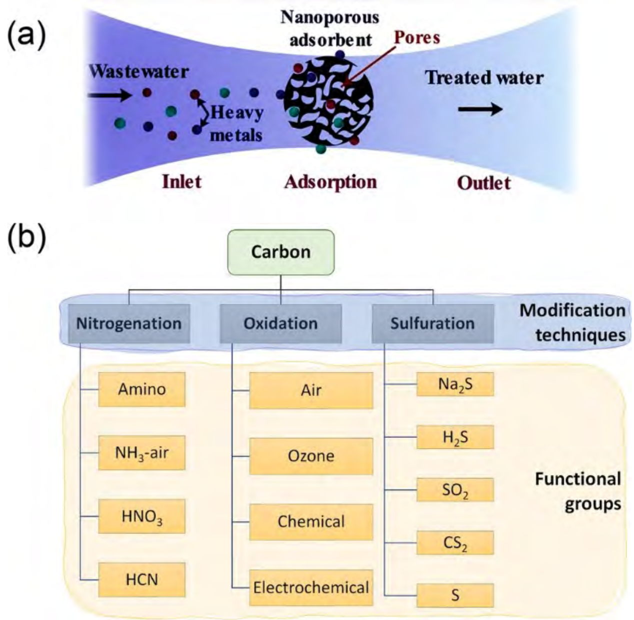

Fig. 3: Adsorption process used for water treatment: (a) Heavy metal ions in wastewater adhere to nanoporous adsorbents with high surface area due to porosity, selectively binding to certain metals. Regeneration is possible using a desorbing agent. (b) Carbon can be modified through techniques like nitrogenation, oxidation, and sulfuration to add functional groups, thereby improving adsorption capacity and stability. (Adapted from Qasem et al. under CCBY Nature 2021)

5. Challenges

Nanofiltration technology offers numerous advantages in water treatment, but it is not without its challenges. Understanding and addressing these challenges is essential for the successful implementation and long-term sustainability of nanofiltration systems. Here, we will discuss some of the key challenges associated with nanofiltration:

Membrane Fouling and Scaling: Fouling: Membrane fouling occurs when particles, microorganisms, or organic matter accumulate on the membrane surface or within its pores. This can reduce filtration efficiency and increase operating costs. Fouling in nanofiltration systems is a significant challenge and requires regular maintenance and cleaning.

Scaling: Scaling is the deposition of inorganic compounds, such as calcium carbonate or sulfate, on the membrane surface, which can lead to reduced permeate flow and increased energy consumption. A study in Desalination (Khalid et al., 2017) discusses the challenges of scaling in nanofiltration and the methods to mitigate it, including antiscalant chemicals and membrane cleaning.

Energy Requirements: While nanofiltration is more energy-efficient than reverse osmosis, it still requires energy to drive the filtration process. Reducing energy consumption is a crucial challenge in making nanofiltration more sustainable. Research in the Journal of Membrane Science (Zhang et al., 2015) explores the optimization of energy consumption in nanofiltration systems.

Selective Contaminant Removal: Nanofiltration's selectivity can be both an advantage and a challenge. While it excels at removing specific contaminants, it may not be equally effective for all types of pollutants. The selective removal of some contaminants may necessitate the use of multiple treatment technologies in conjunction with nanofiltration.

Concentrate Disposal and Brine Management: Nanofiltration generates a concentrate stream (brine) containing concentrated pollutants and rejected solutes. Disposing of brine and managing its environmental impact are challenges, particularly in areas with strict regulations.

The use of nanofiltration for water treatment may be subject to regulatory challenges and the need for standardization. Different regions may have varying standards and regulations related to water quality, which can affect the adoption of nanofiltration.

6. Future outlook: Future Trends and Innovations

Nanofiltration technology has already made significant strides in improving water treatment and addressing various water quality issues. However, the field continues to evolve, and several future trends and innovations are poised to further enhance its efficiency, sustainability, and applicability. The future outlook for nanofiltration holds promising developments in several key areas. One of the most promising trends in nanofiltration is the development of advanced membrane materials. Researchers are working on novel nanomaterials and coatings that can enhance the performance and durability of nanofiltration membranes. These materials aim to reduce fouling, improve selectivity, and extend membrane lifespan. Graphene oxide, carbon nanotubes, and other nanomaterials hold the potential to revolutionize nanofiltration membranes.

7. Conclusion

In conclusion, water treatment using nanofiltration technology represents a sustainable and efficient solution for removing contaminants from wastewater. Nanofiltration offers significant environmental benefits by reducing chemical usage, lowering energy consumption, and minimizing waste generation. It is cost-effective, providing long-term economic savings, and has positive social implications, improving access to clean water and enhancing public health. Despite challenges like membrane fouling, scaling, and regulatory complexities, ongoing innovations, such as advanced membrane materials, resource recovery, and integration with renewable energy, continue to strengthen nanofiltration's potential to address water quality issues, making it a promising technology for a cleaner, healthier future.

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Conflict of Interests

None.

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