

Nano-Adsorbents for Water Purification: A Focus on Nanoclays

Bangshidhar Goswami^{1,*}

Abstract

Nanotechnology has emerged as a pivotal tool in addressing contemporary environmental challenges, particularly in water purification. This paper explores the use of nano-adsorbents, focusing on nano-clay materials, as effective solutions for the adsorption and removal of harmful pollutants from water. Nano-clays, owing to their large surface area and unique physicochemical properties, exhibit exceptional adsorption capacity for contaminants such as heavy metals, dyes, antibiotics, and various organic compounds. This review consolidates the findings from numerous studies on the development and application of nano-clays and their composites for water treatment, emphasizing their preparation techniques, adsorption mechanisms, and practical use in removing hazardous substances from wastewater. Additionally, ceramic membranes doped with halloysite nanoclay are investigated for their efficiency in treating industrial effluents, especially from textile industries. The promising results of these nanomaterials highlight their potential for advancing sustainable and cost-effective water purification technologies, providing an essential pathway for mitigating global water pollution.

Keywords: Adsorption, ceramic membranes, nanoclay, nanocomposites, nano-adsorbents, nanotechnology, water purification

INTRODUCTION

The increasing global demand for clean water, coupled with rising levels of industrial pollution, has created an urgent need for innovative, efficient, and sustainable water treatment solutions. Industrial wastewater, laden with heavy metals, dyes, and organic pollutants, has significantly deteriorated water quality, posing a severe threat to environmental and public health. Traditional water treatment methods often fall short of adequately removing these complex pollutants, leading to the exploration of advanced materials and techniques. Nanotechnology, particularly in the form of nano-adsorbents, has shown immense promise in overcoming these limitations by offering enhanced adsorption capacities and improved efficiencies in contaminant removal.

*Author for Correspondence

Bangshidhar Goswami
E-mail: goswami.b8757@gmail.com

¹Ex-Assistant Professor, Department of Metallurgical Engineering, Ran Vijay Singh College of Engineering and Technology, Jamshedpur, East-Singbhum, Jharkhand, India

Received Date: October 18, 2024

Accepted Date: October 22, 2024

Published Date: November 06, 2024

Citation: Bangshidhar Goswami. Nano-Adsorbents for Water Purification: A Focus on Nanoclays. Journal of Water Pollution & Purification Research. 2024; 11(3): 38–44p.

LITERATURE REVIEW

Nano-Clays for Water Purification

Nano-clays, a class of naturally abundant and low-cost materials, have gained considerable attention due to their high surface area, chemical stability, and tunable adsorption properties. These characteristics make them ideal candidates for water purification applications, where they can effectively capture and immobilize a wide range of pollutants. In parallel, advancements in membrane technologies, such as ceramic membranes doped with halloysite nanoclay, offer complementary solutions by enhancing filtration and separation

processes, particularly in industries with high wastewater output, such as textiles. This paper reviews the current progress in the use of nano-clays and related nanocomposites for water treatment, highlighting their potential to revolutionize conventional water purification techniques and contribute to global environmental sustainability [1].

Nanotechnology's Role in Environmental Protection

Nanotechnology has become integral to modern environmental practices, playing a key role in removing pollutants from water systems. Among the many promising materials, nanoclays have garnered significant attention due to their unique properties and efficiency. Clay, one of the most abundant natural minerals, possesses diverse morphologies and geometries, making it a vital component in environmental protection. For centuries, clay minerals have been used for storage and removal of hazardous substances, as well as for the purification of contaminated water. Their availability, affordability, and high efficiency have made them valuable in industrial applications, including their role as nano-adsorbents in numerous adsorption processes [2].

Adsorption Mechanism in Water Purification

Nanoclay has been shown to be a successful property enhancer for water purification, offering higher removal efficiencies compared to traditional methods. Extensive research has explored its potential for absorbing hazardous substances such as dyes, heavy metals, antibiotics, biocides, and other organic chemicals. This review collates previous and ongoing studies, discussing the innovations in nanoclay technology, future developments, and the adsorption mechanisms employed in various water purification processes. Additionally, the preparation techniques for nanocomposites are highlighted, along with their functional role in enhancing the adsorption process.

Addressing Industrial Water Pollution

The degradation of natural water systems due to industrialization is a pressing global issue. Wastewater generated from industries is a significant source of pollution, impacting aquatic ecosystems and human health. The rapid increase in pollutants discharged into these water bodies includes dissolved solids, heavy metals like arsenic and fluoride, and pathogenic microorganisms. Access to clean drinking water is a critical health determinant for communities worldwide. However, traditional water purification techniques often fall short in eliminating the increasing load of hazardous pollutants. This calls for the development of cost-effective and efficient water treatment technologies that rely on environmentally friendly materials [3, 4].

Nanoclay and Ceramic Membrane Applications

Nanotechnology provides solutions for many of these challenges. By manipulating materials at the nanoscale, new properties can be harnessed that significantly improve water purification methods. Nanoscale materials like nanoclays, in particular, offer a promising route to filter out harmful contaminants from water. Their high surface area and unique structural properties make them effective for adsorbing metal ions, organic and inorganic solutes, and even microbiological contaminants. Research has demonstrated the utility of a variety of nanomaterials—such as zeolites, dendrimers, carbonaceous nanomaterials, and metal-containing nanoparticles—in water treatment applications. Nanoclays stand out among these for their efficiency and environmental friendliness [5].

Performance of Nanoclay-Based Adsorbents

Recent advancements in nanoclay materials have further cemented their role as essential adsorbents for water purification. This study set out to evaluate the effectiveness of clay and nanoclay granules in improving water's physicochemical and biological properties. The study prepared 5-mm diameter clay granules with a 50% clay-nanoclay composition, heated to 1000°C for seven hours, and immersed them in 300 mL of artificially contaminated water for 24 hours. Results showed significant reductions in lead, nitrate, arsenic, and turbidity, with nanoclay demonstrating an 88% adsorption

yield for lead compared to 80% for clay granules. Though microbial contamination remained unresolved, the findings illustrate nanoclay's superior performance over traditional clay in adsorption processes.

Ceramic Membranes in Water Treatment: Enhanced Performance with Nanoclay Doping

Ceramic membranes have emerged as a viable technology for advanced water purification, offering advantages in durability, chemical resistance, and the ability to operate under extreme conditions such as high temperatures and pressures. One of the key areas of innovation in this field is the incorporation of nanoclays into the membrane matrix. By doping ceramic membranes with nanoclays, their filtration capabilities and overall performance can be significantly enhanced, making them highly effective for treating industrial wastewater [6].

Production of Ceramic Membranes

In this study, ceramic membranes were produced using a sequential layer deposition method at low temperatures. This process involves applying thin layers of materials sequentially onto a ceramic substrate to form a membrane structure. The low-temperature deposition technique is crucial for maintaining the structural integrity of the nanoclay and ensuring uniform distribution across the membrane's surface. This layered structure contributes to the improved filtration properties of the membrane, allowing for better separation of pollutants from wastewater.

Application to Textile Industry Wastewater

The membranes were tested using real wastewater samples from the textile industry, which is notorious for generating large volumes of highly polluted wastewater. Textile effluents often contain a complex mixture of organic dyes, chemicals, and heavy metals, making them challenging to treat with conventional water purification methods. The study specifically targeted the removal of several key pollutants from the wastewater, including bovine serum albumin (BSA), chemical oxygen demand (COD), total organic carbon (TOC), and color [7].

Bovine serum albumin was chosen as a test compound because of its large molecular size, which makes it a representative indicator of the membrane's ability to filter out proteins and similar organic contaminants. COD and TOC were measured to assess the overall organic load in the water, as they represent the total amount of oxygen required to chemically decompose organic compounds (COD) and the total amount of organic carbon present (TOC). These are critical parameters in determining water quality and the effectiveness of the purification process [8].

Performance of Tight-Ultrafiltration Membranes

The nanoclay-doped ceramic membranes were evaluated for their filtration performance under various conditions. The tight-ultrafiltration membranes, which have pore sizes on the nanometer scale, showed a significant capability to remove a wide range of contaminants. Specifically, these membranes achieved a removal efficiency exceeding 40% for COD and TOC. This indicates that the membranes were effective at capturing and eliminating a substantial portion of the organic pollutants from the textile wastewater. In addition to removing organic compounds, the membranes also displayed a high capacity for decolorizing the wastewater, which is a major concern in textile effluent treatment due to the presence of synthetic dyes.

Flux Performance in Hot Wastewater

A major challenge in industrial water treatment lies in balancing filtration efficiency with the flow rate, or flux, of water through the membrane. Flux, measured as the volume of water filtered per unit area over time, is crucial for determining how efficiently a system can process large volumes of water, especially in industrial environments where continuous, large-scale treatment is required. In industries such as textiles, petrochemicals, or food processing, wastewater is often discharged at elevated temperatures, which can complicate filtration efforts and reduce membrane efficiency over time [9].

Impact of Temperature on Flux

Temperature plays a significant role in the performance of filtration membranes. Higher temperatures typically lower the viscosity of wastewater, allowing water molecules to pass more easily through the membrane's pores. However, high temperatures can also degrade membrane materials, decrease selectivity, and cause fouling, which would reduce the membrane's ability to retain contaminants. Therefore, maintaining or improving flux at elevated temperatures without compromising filtration efficiency is an essential goal for any advanced membrane technology.

In this study, the performance of nanoclay-doped ceramic membranes was evaluated under conditions of elevated temperature using real wastewater from the textile industry. The results showed that the flux increased threefold in hot wastewater compared to ambient conditions. This is a substantial improvement, highlighting the membrane's ability to handle high-temperature wastewater streams effectively.

Mechanisms Behind Increased Flux in Hot Wastewater

Several mechanisms likely contribute to the *enhanced flux performance* observed in hot wastewater conditions:

1. *Reduced water viscosity:* As the temperature of the wastewater increases, its viscosity decreases, allowing for easier and faster passage of water molecules through the membrane pores. This reduced resistance to flow enhances the overall flux without requiring additional energy inputs.
2. *Improved mass transport:* Higher temperatures can also promote better *mass transport* within the membrane, facilitating faster diffusion of contaminants to the adsorption sites on the nanoclay surface. This reduces the buildup of pollutants on the membrane surface, which can otherwise lead to fouling and reduced filtration performance.
3. *Thermal resilience of nanoclay-doped membranes:* The nanoclay doping contributes to the *thermal resilience* of the ceramic membranes, ensuring that they maintain structural integrity and performance even under elevated temperatures. Nanoclay materials, such as halloysite and montmorillonite, possess high thermal stability, making them well-suited for use in high-temperature industrial environments. The ceramic matrix further reinforces this stability, preventing deformation or damage that could compromise the membrane's filtration capabilities.

Contaminant Removal Efficiency at High Flux

A key finding from the study was that the significant increase in flux did not compromise the membrane's ability to remove contaminants. Often, when flux is increased in filtration systems, there is a trade-off in the quality of filtration, as higher flow rates can reduce the contact time between contaminants and the membrane's active sites, leading to incomplete removal. However, in this case, the nanoclay-doped ceramic membranes maintained their high filtration efficiency even at elevated flux levels.

This finding suggests that the membranes were able to sustain effective contaminant removal through a combination of nanoclay adsorption and tight-ultrafiltration mechanisms. Nanoclays, with their high surface area and excellent adsorption properties, played a crucial role in capturing organic pollutants, heavy metals, and other contaminants. The ceramic matrix provided a robust filtration framework, ensuring that fine particulates and dissolved solids were effectively filtered out, even at higher flow rates.

Industrial Implications: Handling Hot Wastewater

The ability to process hot wastewater efficiently is particularly important for industries where water is used in large volumes and discharged at elevated temperatures. Textile wastewater, for example, is

typically released at high temperatures due to the use of hot water in dyeing, washing, and rinsing processes. Treating this water without first cooling it can save both energy and operational costs.

The threefold increase in flux observed in this study means that these nanoclay-doped ceramic membranes could handle larger volumes of wastewater in less time, thereby improving the overall throughput of the water treatment system. This capability is particularly valuable for industries that generate wastewater continuously and at high volumes, as it minimizes downtime and reduces the energy consumption associated with water treatment processes.

Moreover, the ability to maintain effective contaminant removal while increasing flux provides an added advantage in terms of cost efficiency. Membranes that can operate efficiently at high temperatures reduce the need for additional pre-treatment steps, such as cooling or dilution, which are often required to protect less thermally stable membranes. This reduces both the operational complexity and the associated costs, making nanoclay-doped ceramic membranes a highly attractive solution for large-scale industrial applications.

Future Potential for High-Temperature Industrial Wastewater Treatment

The study's findings point to significant potential for the application of nanoclay-doped ceramic membranes in treating hot, contaminated wastewater across a variety of industries. Beyond textiles, sectors such as oil and gas, chemical manufacturing, and food processing often produce wastewater with elevated temperatures and high pollutant loads. The membranes' demonstrated ability to maintain high filtration performance under these conditions positions them as a promising technology for sustainable and cost-effective wastewater treatment.

Further research could explore the long-term stability of these membranes in continuous operation and under extreme conditions, as well as their adaptability to different types of industrial wastewater. Optimizing the nanoclay composition, pore size distribution, and layer deposition methods could further enhance their performance, making them even more effective for a wide range of water treatment applications.

In conclusion, the nanoclay-doped ceramic membranes' ability to handle hot wastewater efficiently, with increased flux and maintained contaminant removal, makes them a highly promising technology for industries that require reliable, high-volume water treatment. Their thermal resilience, combined with the natural adsorption properties of nanoclays, offers a significant advantage in addressing the challenges of industrial wastewater management in high-temperature environments.

Advantages of Nanoclay-Doped Ceramic Membranes

The incorporation of nanoclays into ceramic membranes offers several benefits that make them highly suitable for large-scale industrial applications. Nanoclays, such as halloysite, provide a high surface area and unique adsorption properties, which enhance the membranes' ability to trap contaminants. The structural and chemical properties of nanoclays improve the membrane's selectivity, enabling it to remove a wide variety of pollutants, including heavy metals, organic compounds, and dyes.

Moreover, the mechanical strength and thermal stability of ceramic membranes are preserved or even improved with nanoclay doping, allowing them to withstand harsh industrial conditions. These characteristics make them ideal for industries like textiles, where wastewater often contains high concentrations of difficult-to-treat pollutants and must be processed under demanding conditions.

Industrial Implications and Future Potential

The findings from this study suggest that nanoclay-doped ceramic membranes are a promising solution for addressing the pressing issue of wastewater treatment in industries like textiles. Their

ability to efficiently remove a range of organic pollutants, coupled with their enhanced flux and durability, positions them as a valuable technology for large-scale industrial wastewater management [10].

As environmental regulations become more stringent and industries seek sustainable methods for managing wastewater, the development and deployment of advanced ceramic membranes with nanoclay additives will likely play a crucial role. Further research into optimizing the membrane structure, nanoclay content, and operating conditions could unlock even greater efficiencies, making this technology a cornerstone of future water treatment systems.

Impact on Textile Industry Wastewater

The textile industry is one of the largest consumers of water, discharging vast quantities of wastewater laden with hazardous dyes and chemicals. Traditional treatment methods—such as flocculation, ozonation, and biological decomposition—are inadequate for dealing with the wide variety of dyes used in textile processes. Membrane technologies, particularly those enhanced with nanomaterials, provide a more sustainable and efficient solution. Ceramic membranes with nanoclay coatings have been shown to remove over 98% of reactive dyes from synthetic wastewater. These membranes leverage nanoclay's unique adsorption properties to improve dye removal efficiency, while the membrane structure provides enhanced durability and stability.

Material Science Perspective on Nanoclays

In terms of material science, nanoclay offers additional benefits due to its structure and composition. Halloysite nanoclay (HNT), for instance, is an aluminum silicate clay that is abundant in nature and relatively inexpensive. Its tubular structure, combined with a high surface area and hydrophilicity, makes it particularly effective in removing anionic dyes from water. Studies have shown that HNT can remove acidic and direct dyes from textile wastewater with high efficiency, making it a valuable tool in industrial water treatment.

Future Directions in Nanoclay Technologies

Valorizing nanoclays through advanced processing techniques has also expanded their applicability. By optimizing firing temperatures and processing methods, nanoclay-based materials can be fine-tuned for use in specific industrial applications. For example, the ceramic tile industry in Tunisia has explored the use of nanoclay to enhance the properties of tiles, achieving improvements in strength, shrinkage, and water absorption. The potential of nanoclay as a multifunctional material for environmental applications is thus well-established.

CONCLUSION

Nanotechnology, particularly the use of nano-adsorbents such as nanoclay and nanocomposites, has emerged as a promising solution for water purification. The unique properties of nanomaterials, including high surface area and enhanced adsorption efficiency, make them highly effective in removing hazardous contaminants such as heavy metals, dyes, and other organic pollutants from water. The research highlights the significant potential of nanoclays in improving water treatment processes, outperforming traditional materials in various applications. Additionally, the integration of ceramic membranes doped with nanoclays has proven effective in enhancing filtration performance, especially in industrial wastewater treatments. While challenges remain in terms of cost and scalability, continuous innovation and research in nanotechnology are paving the way for more efficient, environmentally friendly, and cost-effective water purification methods. These advancements hold great promise for addressing the global challenge of clean water accessibility, contributing to sustainable environmental protection.

REFERENCES

1. Awasthi A, Jadhao P, Kumari K. Clay nano-adsorbent: structures, applications and mechanism for water treatment. *SN Applied Sciences*. 2019 Sep;1(9):1076.
2. Rezvani P, Taghizadeh MM. On using clay and nanoclay ceramic granules in reducing lead, arsenic, nitrate, and turbidity from water. *Applied Water Science*. 2018 Sep;8(5):131.
3. Ağtaş M, Dilaver M, Koyuncu I. Halloysite nanoclay doped ceramic membrane fabrication and evaluation of textile wastewater treatment performance. *Process Safety and Environmental Protection*. 2021 Oct 1;154:72-80.
4. Moussi B, Hajjaji W, Hachani M, Hatira N, Labrincha JA, Yans J, Jamoussi F. Numidian clay deposits as raw material for ceramics tile manufacturing. *Journal of African Earth Sciences*. 2020 Apr 1;164:103775.
5. Cai X, Madari S, Walker A, Paiva A, Li Y, Herbst J, Shou W, Weller H. Addition of optimized bovine serum albumin level in a high-throughput Caco-2 assay enabled accurate permeability assessment for lipophilic compounds. *SLAS DISCOVERY: Advancing Life Sciences R&D*. 2019 Aug;24(7):738-44.
6. Lellis B, Fávaro-Polonio CZ, Pamphile JA, Polonio JC. Effects of textile dyes on health and the environment and bioremediation potential of living organisms. *Biotechnology Research and Innovation*. 2019 Jul 1;3(2):275-90.
7. Collins CE, Incropera FP, Grady Jr CP. The effect of temperature control on biological wastewater treatment processes. *Water Research*. 1978 Jan 1;12(8):547-54.
8. Zhang T, Wang W, Zhao Y, Bai H, Wen T, Kang S, Song G, Song S, Komarneni S. Removal of heavy metals and dyes by clay-based adsorbents: From natural clays to 1D and 2D nanocomposites. *Chemical Engineering Journal*. 2021 Sep 15;420:127574.
9. Miele D, Ruggeri M, Vigani B, Viseras C, Natali F, Del Favero E, Rossi S, Sandri G. Nanoclay-doped electrospun nanofibers for tissue engineering: investigation on the structural modifications in physiological environment. *International Journal of Nanomedicine*. 2023 Dec 31:7695-710.
10. Subburaj S, Paramasivam M, Lafta MH, Gangadhar L. A Review on Elimination of Colour and Dye Products from Industrial Effluent. *Water Purification-Present and Future*. 2024 Apr 18.