Deep Science Publishing, 2025
https://doi.org/10.70593/978-93-7185-662-1_6

Chapter 6: Nanostructured Materials for Sustainable Water Purification Systems

Akshay Chavan[1*], Sanket Ghule[2], Pooja More[3]

[1]Department of Environmental Science, School of Earth Sciences, Punyashlok Ahilyadevi Holkar Solapur University, Solapur, Maharashtra*
[2]. Ascent College, Kandalgaon, Tal. South Solapur, Solapur, Maharashtra
[3]. Ascent College, Kandalgaon, Tal. South Solapur, Solapur, Maharashtra

Corresponding Author E-Mail Id: achavan95@gmail.com

Abstract: Access to clean and safe water remains a critical global challenge, particularly in developing nations where conventional purification technologies often fail to meet growing demands. In recent years, nanostructured materials have emerged as promising candidates for sustainable water purification due to their high surface area, tunable properties, and reactivity at the nanoscale. This paper reviews the development and application of various nanostructures—including carbon-based nanomaterials, metal and metal oxide nanoparticles, nanocomposites, and polymeric nanomembranes—in addressing contaminants such as heavy metals, pathogens, organic pollutants, and emerging micro/nano-pollutants. The mechanisms involved, such as adsorption, photocatalysis, and membrane filtration, are discussed along with environmental and safety concerns. The paper also highlights innovations in scalable green synthesis and the potential for integrating nanotechnology into decentralized and low-energy water treatment systems.

Keywords: Nanomaterials, water purification, photocatalysis, adsorption, nanocomposites, sustainability, membrane filtration.

1 Introduction

1.1 Background and Motivation

The pollution of freshwater by industrial effluents, agricultural runoff, and domestic sewage poses significant threats to the environment and human health. Over 2 billion people around the globe lack access to safely managed drinking water (WHO, 2023). Traditional treatment technologies such as chlorination, sand filtration, and reverse osmosis consistently fail to eliminate complex or trace levels of contaminants, especially heavy metals, pharmaceuticals, pesticides, and pathogens (Shannon et al., 2008). The worsening world water crisis due to pollution, climate change, and swelling populations calls for the testing and implementation of improved water purification technologies (Patanjali et al., 2019). Nanotechnology, through the possibility of material manipulation at the nano level, provides radical solutions for overcoming those challenges and delivering clean and cheap water (Qu et al., 2013; Singh et al., 2021). Nanostructured materials, characterized by their characteristic physicochemical behavior depending on their size and shape, have emerged as potential hopes for improving the efficiency and sustainability of water treatment systems (Benettayeb et al., 2023; Soni et al., 2020). Nanostructured materials possess high surface areas per volume, quantum phenomena, and modifiable surface functionalities and therefore can interact with contaminants in aquatic systems more selectively and efficiently (Singh et al., 2021). Nanomembranes, nanoadsorbents, nanocatalysts, and nanostructured photocatalysts are the nanoconstruction based materials that are under investigation for water treatment (Gehrke et al., 2015). It reviews the latest progresses in the use of nanostructured materials for waters decontamination including preparation, characterization, performance, and perspectives for the environment. Nanoadsorbents such as nanoparticles, nanotubes, and nanofibers are efficient in the adsorption of a wide range of contaminants such as heavy metals, organic molecules, and pathogens (Kumar et al., 2014; Theron et al., 2008). High surface areas, and designed surface chemistries allow for high interaction with the target pollutant with the material, and these in turn lead to high performance materials for pollutant removal from water (Lu et al.,, 2016).

The increasing worldwide water crisis, which is manifested by water stress and pollution, and threats water-related human health, economic development and environmental sustainability (Gehrke, et al., 2015). Urbanization, industrialization, and climate change contribute to water scarcity, which is defined as a lack of available water to meet the needs of a population within a specific region. Rapid Urbanization and Industrialisation

Have Facilitated Increased Freshwater Demand And Wastewater Generation, Imposing Unprecedented Pressure On Freshwater Resources. Classical methods, however, are generally inadequate for this purpose, on a global basis, in the case of emerging contaminants including pharmaceuticals, personal care products, and endocrine disruptors, which have significant impacts in terms of human health and aquatic ecosystems at trace levels. In addition, the conventional treatment is generally high energy demanding, chemical based and produces a large amount of sludge, so that in some extent raising serious doubt on its environmental friendliness and cost effectiveness. In addition, conventional water utilities are highly infrastructural dependent and technology-driven as they require highly-skilled personnel and are therefore unsuitable for decentralised or point-of-use settings such as the developing world. It is because the shortcoming of the conventional methods for waste water treatment in order to overcome a better and sustainable treatment system, at low energy consumption, least use of chemicals and decentralized waste water treatment which can remove a wide spectrum contaminant.

Applications of nanotechnology heralding a new dawn in the management of wastewater and water resources through efficiency enhancement and supplementation of traditional water sources with non-traditional water sources like water reuse (Qu et al., 2013). Nanotechnology, which entails manipulating matter at the atomic or molecular level (1–100 nm), has promising attributes for the advancement of water purification processes, because many contaminants have particle-size characteristic in the range of nanometer. Thanks to their unique characteristics at the physicochemical level, nanomaterials have a series of merits over the traditional treatment technology, such as removal efficiency, energy consumption, and selectivity for pollutants. Nanomaterials are useful for the removal of different pollutants, such as bacteria and pollutants (Sharma, 2021). Nanomaterials are antimicrobial reverse osmosis agents and used in this field to remove the pollutant particles and pathogenic organisms including nano-biotechnology/link with conventional techniques that tremendously try to resolve the contamination or drinking water limitations (either alone or in combination; Rafique et al., 2019; Sahu et al., 2019). Therefore, among the various nanomaterials developed, nanoadsorbents, nanomembranes, nanocatalysts, and nanostructured photocatalysts can be introduced as the main classes of nanomaterials that are currently under study and considered to be used in water applications (Qu et al., 2013). The science of nanotechnology can provide novel solutions for the problem of water purification by homing nanostructured-materials able to work in an extremely broad range of contaminants and to do so with high specificity, efficiency, and reusability. Such materials can be fabricated to have special physicochemical properties such as:

- High surface-to-volume ratios
- Enhanced reactivity
- Catalytic behavior under ambient conditions
- Selective adsorption capabilities

1.2 Role of Nanostructured Materials

Nanostructured materials have found applications in:

- Adsorption of heavy metals and dyes using activated carbon nanotubes
- Disinfection via silver or copper nanoparticles
- Photocatalytic degradation of organic pollutants using TiO_2 or ZnO
- Nanofiltration membranes with improved fouling resistance and permeability

The integration of these materials into modular and decentralized systems has the potential to revolutionize point-of-use and community-level water purification in low-resource settings.

1.3 Objective and Scope

This review aims to:

- Provide an overview of various nanostructured materials used in water purification.
- Discuss mechanisms such as adsorption, catalysis, and membrane separation.
- Evaluate the sustainability and toxicity aspects of nanomaterials.
- Highlight innovations in green synthesis and implementation challenges.
- Recommend future directions for research and deployment at scale.

2 Classification and Mechanisms of Nanostructured Materials

Nanostructured materials are categorized based on their morphology, chemical composition, and the specific mechanisms through which they interact with water contaminants. Below is an overview of the major classes and their associated purification functions.

2.1 Carbon-Based Nanomaterials

2.1.1 Carbon Nanotubes (CNTs)

- Mechanism: Adsorption and filtration through large surface area and π–π stacking interactions.
- Applications: Removal of dyes, pharmaceutical residues, and heavy metals like Pb^{2+} and Cd^{2+}.
- Advantages: High adsorption capacity and mechanical strength.

2.1.2 Graphene and Graphene Oxide (GO)

- Mechanism: Surface adsorption via oxygen-containing functional groups.
- Applications: Efficient in removing As^{3+}, Hg^{2+}, and emerging organic contaminants.
- Limitations: Aggregation in aqueous systems unless supported or functionalized.

2.2 Metal and Metal Oxide Nanoparticles

2.2.1 Silver (Ag) and Copper (Cu) Nanoparticles

- Mechanism: Antimicrobial action via ion release and oxidative stress.
- Applications: Disinfection of bacterial and viral pathogens.
- Considerations: Risk of nanoparticle leaching and cytotoxicity.

2.2.2 Titanium Dioxide (TiO2) and Zinc Oxide (ZnO)

• Mechanism: Photocatalysis under UV/visible light leading to the formation of reactive oxygen species (ROS) and the degradation of organics.

• Applications: Oxidation of phenols, dyes and endocrine disruptor compounds.

• Enhancement: Nonmetal doping (N and F) promotes visible light activity.

2.3 Polymeric and Inorganic Nanocomposites

• Composition: NP including nanoparticles (e.g., Ag, Fe_3O_4) mixed with polymer matrices (e.g., chitosan, polyvinyl alcohol).

• Mechanism: The synergistic effects of enhanced adsorption, catalytic degradation, and mechanical stability.

• Applications: Multi-contaminant removal by hybrid filters.

2.4 Magnetic Nanoparticles (Fe_3O_4, $MnFe_2O_4$)

- Mechanism: Adsorption of heavy metals followed by magnetic separation.
- Advantage: Easy recovery and reuse using external magnets.
- Applications: Arsenic, fluoride, and phosphate removal.

2.5 Nanostructured Membranes

- Types: Electrospun nanofibers, thin-film nanocomposite (TFN) membranes.
- Function: Nanofiltration and ultrafiltration for removal of bacteria, viruses, and salts.
- Properties: Enhanced permeability, anti-fouling behavior, and mechanical robustness.

Table-01 Applications of Nanomaterials in Environmental Remediation

Nanomaterial	Primary Mechanism	Target Contaminants	Notable Features
CNTs	Adsorption	Dyes, heavy metals	High surface area
Ag/Cu nanoparticles	Antimicrobial	Bacteria, viruses	Broad-spectrum disinfection
TiO_2/ZnO	Photocatalysis	Organics, pesticides	Visible light activation possible
Fe_3O_4 nanoparticles	Adsorption & magnetic	Arsenic, phosphate	Recyclable with external magnet
TFN membranes	Filtration	Pathogens, organics, salts	High permeability, antifouling resistance

Table-01 shown nanomaterials play a crucial role in modern environmental remediation strategies (Table 4). Carbon nanotubes (CNTs) provide a large surface area for adsorption, making them effective in removing dyes and heavy metals. Similarly, Fe_3O_4 nanoparticles combine adsorption with magnetic properties, enabling both arsenic and phosphate removal while allowing for easy recyclability using an external magnet. Metal-based nanomaterials such as Ag and Cu nanoparticles demonstrate strong antimicrobial activity against bacteria and viruses, offering broad-spectrum disinfection potential. Meanwhile, semiconductor nanomaterials like TiO_2 and ZnO leverage photocatalysis to degrade organic pollutants and pesticides, with the added advantage of visible light activation.

3 Sustainability, Toxicity, and Green Synthesis of Nanomaterials

As the use of nanomaterials in water treatment increases, it is critical to evaluate their **environmental sustainability**, **human health risks**, and the **ecological footprint** of their synthesis and disposal.

3.1 Environmental Sustainability

Nanomaterials support sustainable development goals (SDGs) in water sanitation by:

- Improving **contaminant removal efficiency**
- Enabling **point-of-use** and **low-energy** water treatment systems
- Providing **modular solutions** for decentralized settings

3.2 Toxicological Considerations

Despite their advantages, certain nanomaterials may pose risks:

- **Metal nanoparticles** (e.g., Ag, ZnO) may release ions that are cytotoxic to aquatic organisms.
- **Carbon-based nanomaterials** can accumulate in biological tissues if not properly functionalized.
- **Nanoparticle leaching** from membranes or filters can lead to unintended exposure.

Mitigation Measures:

- Surface functionalization to reduce bioavailability
- Immobilization within solid matrices (e.g., hydrogels, composites)
- Development of **biodegradable nanomaterials**

3.3 Green Synthesis Approaches

Green chemistry principles are increasingly being applied to the synthesis of nanomaterials using:

- **Plant extracts** (green tea, neem, etc.) as reducing agents for metal nanoparticle synthesis
- **Biopolymers** (e.g., chitosan, alginate) for encapsulation and support
- **Microwave or sonochemical methods** for energy-efficient fabrication

Example: Silver nanoparticles synthesized using *Azadirachta indica* (neem) extract demonstrated antibacterial properties with reduced cytotoxicity (Raghunandan et al., 2011).

These approaches reduce:

- Use of hazardous solvents (e.g., ethanol over toluene)
- Generation of toxic by-products
- Energy consumption during production

3.4 Life Cycle Assessment (LCA)

Recent LCA studies have evaluated:

- Carbon footprint of nanomaterial synthesis
- Comparative analysis of nanofiltration vs. RO systems
- Trade-offs between performance and material safety

4 Case Studies, Innovations, and Future Directions

A few of the implementation of the nanostructured materials in actual water purification systems is also described to show the fantabulous scenic view of the planetary phenomena to the reality. While in India, a community-based filter with MWnt were used in uttar pradesh rural villages to mitigate arsenic and iron. These filters performed extremely well by reducing the levels of the contaminants below even the WHO limit, and could operate successfully for more than 12 months without any significant drop in livability. Silver nanoparticles (AgNPs) were also used and the capacity of AgNP embedded ceramic tablets for removal of pathogens from rural water supply in Sub-Saharan Africa was >99% . This approach not only ensured safe drinking water but also demonstrated advantages in terms of scalability and low maintenance, making it particularly suitable for resource-limited settings. Another notable innovation has been the integration of TiO_2-based photocatalytic units with solar energy in Southern India. Rooftop systems coated with TiO_2 harnessed solar irradiation to degrade pesticide residues such as carbaryl and atrazine in agricultural runoff, achieving more than 80% contaminant reduction. These case studies underscore the practical viability of nanomaterials in diverse contexts, from decentralized village-level purification to agricultural water treatment, and demonstrate their ability to address both chemical and biological contaminants in a sustainable manner.

Table-02 Challenges and Research Gaps

Area	Current Limitation	Required Research
Long-term stability	Nanomaterials degrade or leach over time	Surface coating and matrix stabilization
Cost of fabrication	High for advanced materials	Biosourced, low-energy synthesis
Regulatory framework	Sparse or absent in many countries	Development of nanomaterial safety standards
Public awareness	Limited adoption due to lack of familiarity	Training, education, and community engagement

Despite the promising applications of nanomaterials in water treatment, several challenges and research gaps remain (Table 2). One of the key concerns is the long-term stability of these materials, as many nanomaterials tend to degrade or leach into water over extended use, potentially posing secondary risks. Addressing this issue requires innovations such as surface coatings and incorporation into stable matrix supports. Another major limitation is the cost of fabrication, which remains high for advanced nanomaterials; therefore, research into biosourced precursors and low-energy synthesis methods is essential to improve affordability.

4.6 Future Directions

- **Design for end-of-life**: Recyclable and biodegradable nanomaterials
- **Multi-functionality**: Combining purification with **desalination**, **sensing**, and **energy harvesting**
- **Global collaboration**: Open-access platforms to share data, synthesis methods, and field results

Conclusions

The rapidly growing global water crisis driven by scarcity and polluted supplies underlines the importance of novel and upcoming advanced purification methods that go beyond traditional horizons. Nanotechnology offers not only a disruptive solution by providing highly efficient contaminant removal (pathogens, emerging contaminants, etc.) due in part to the unique properties of nanomaterials such as high surface area, and tunable functions. Nanoadsorbents, nanomembranes, and nanocatalysts offer improvements in terms of efficiency and sustainability in water treatment in many contexts, from point-of-use devices to wastewater, and desalination.

However, the progress is not straightforward and most of them are very challenging: scalability, cost-efficiency, sustained stability and comprehensive cognition of environmental and health effects are posed as tough problems. Finding solutions for these challenges will demand intensive research in sustainable syntheses, advanced characterization and life cycle assessments. To succeed in the future will require creativity, and some luck to triumph over these challenges through inter- and multi- and transdisciplinarity, and by helping to create regulatory environments that firmly place nanotechnology at the vanguard of a benevolent solution which will grant access to clean safe water to the world of tomorrow.

References

Aljedaani, R. O., Kosa, S. A., & Salam, M. A. (2022). Ecofriendly Green Synthesis of Copper (II) Oxide Nanoparticles Using Corchorus olitorus Leaves (Molokhaia) Extract and Their Application for the Environmental Remediation of Direct Violet Dye via Advanced Oxidation Process. Molecules, 28(1), 16. https://doi.org/10.3390/molecules28010016

Benettayeb, A., Seihoub, F. Z., Pal, P., Ghosh, S., Usman, M., Chia, C. H., Usman, M., & Sillanpää, M. (2023). Chitosan Nanoparticles as Potential Nano-Sorbent for Removal of Toxic Environmental Pollutants [Review of Chitosan Nanoparticles as Potential Nano-Sorbent for Removal of Toxic Environmental Pollutants]. Nanomaterials, 13(3), 447. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/nano13030447

Chahar, M., Khaturia, S., Singh, H. L., Solanki, V. S., Agarwal, N., Sahoo, D. K., Yadav, V. K., & Patel, A. (2023). Recent advances in the effective removal of hazardous pollutants from wastewater by using nanomaterials—A review. Frontiers in Environmental Science, 11. https://doi.org/10.3389/fenvs.2023.1226101

Gehrke, I., Geiser, A., & Somborn-Schulz, A. (2015). Innovations in nanotechnology for water treatment [Review of Innovations in nanotechnology for water treatment]. Nanotechnology Science and Applications, 1. Dove Medical Press. https://doi.org/10.2147/nsa.s43773

González-Jartín, J. M., Alfonso, A., Alvariño, R., Rodríguez-Cañás, I., Vieytes, M. R., Piñeiro, Y., Alves, L. de C., González-Gómez, M. A., Rivas, J., & Botana, L. M. (2022). Green Nanotechnology for the Remediation of Cyanotoxins from Contaminated Waters. 12. https://doi.org/10.3390/blsf2022014012

Kumar, S., Ahlawat, W., Bhanjana, G., Heydarifard, S., Nazhad, M. M., & Dilbaghi, N. (2014). Nanotechnology-Based Water Treatment Strategies [Review of Nanotechnology-Based Water Treatment Strategies]. Journal of Nanoscience and Nanotechnology, 14(2), 1838. American Scientific Publishers. https://doi.org/10.1166/jnn.2014.9050

Lu, H., Wang, J., Stoller, M., Wang, T., Bao, Y., & Hao, H. (2016). An Overview of Nanomaterials for Water and Wastewater Treatment. Advances in Materials Science and Engineering, 2016, 1. https://doi.org/10.1155/2016/4964828

Patanjali, P. K., Singh, R., Kumar, A., & Chaudhary, P. (2019). Nanotechnology for water treatment: A green approach. In Elsevier eBooks (p. 485). Elsevier BV. https://doi.org/10.1016/b978-0-08-102579-6.00021-6

Qu, X., Alvarez, P. J. J., & Li, Q. (2013). Applications of nanotechnology in water and wastewater treatment [Review of Applications of nanotechnology in water and wastewater treatment]. Water Research, 47(12), 3931. Elsevier BV. https://doi.org/10.1016/j.watres.2012.09.058

Rafique, M., Tahir, M. B., & Sadaf, I. (2019). Nanotechnology: An Innovative Way for Wastewater Treatment and Purification. In Nanotechnology in the life sciences (p. 95). Springer International Publishing. https://doi.org/10.1007/978-3-030-02381-2_5

Sahu, J. N., Karri, R. R., Zabed, H. M., Shams, S., & Qi, X. (2019). Current Perspectives and Future Prospects of Nano-Biotechnology in Wastewater Treatment. Separation and Purification Reviews, 50(2), 139. https://doi.org/10.1080/15422119.2019.1630430

Sharma, R. (2021). Nanotechnology: an approach for water purification-review. IOP Conference Series Materials Science and Engineering, 1116(1), 12007. https://doi.org/10.1088/1757-899x/1116/1/012007

Singh, N., Malik, M. A., & Hashmi, A. A. (2021). Nanotechnology and its Application in Wastewater Treatment (p. 307). https://doi.org/10.1002/9781119818915.ch13

Soni, R., Pal, A. K., Tripathi, P., Lal, J. A., Kesari, K. K., & Tripathi, V. (2020). An overview of nanoscale materials on the removal of wastewater contaminants. Applied Water Science, 10(8). https://doi.org/10.1007/s13201-020-01275-3

Theron, J., Walker, J. A., & Cloete, T. E. (2008). Nanotechnology and Water Treatment: Applications and Emerging Opportunities [Review of Nanotechnology and Water Treatment: Applications and Emerging Opportunities]. Critical Reviews in Microbiology, 34(1), 43. Taylor & Francis. https://doi.org/10.1080/10408410701710442