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# Environmental Remediation Applications of Nanocomposites on Water Pollution

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**ABSTRACT:** Economic growth was followed by industrialization and population expansion, which led to an increased demand for goods, energy, food, and water. While this contributed to rapid global development, it also severely polluted the Earth, especially the air, water, and soil. Water pollution, in particular, is critical, as water is essential for both human and animal life. However, the discharge of industrial waste, effluents, agricultural runoff, and untreated sewage into water bodies has become a widespread issue, leading to serious health consequences for humans and damage to ecosystems. To address this problem, the use of nanocomposites has emerged as a promising solution for the remediation of harmful substances and the restoration of natural environments. This new-age technology employs a variety of nanocomposite materials designed to target different stages of water pollution. These include electrospun nanofibrous membranes for the removal of heavy metals, nanocomposite membranes for wastewater filtration, polymer-based nanocomposites that degrade water pollutants and inhibit microbial growth, natural nanocomposites derived from reusable materials with minimal environmental impact, and magnetic nanocomposites for water purification. Due to their high efficiency, cost-effectiveness, environmental compatibility, and adaptability, these materials have the potential to serve as sustainable third-generation water treatment technologies. Thus, the general application of nanocomposites in environmental protection and the decontamination of water pollutants, with respect to their sources, fate, and effects on human health, is increasingly being explored and reviewed.

**KEYWORDS:** Nanocomposites; water pollution; environmental remediation; heavy metal removal; wastewater treatment; nanofiltration membranes

## 1. Introduction

With rapid industrialization, technological advancement, and population growth, environmental pollution emerged as a pressing global concern due to the increased demand for resources and the pollutants produced to meet these demands. Whether for energy, primarily through the increased use of fossil fuels, or for goods and services, all of these factors contributed to global pollution, which harmed not only human health but also the environment. Among these concerns, water pollution stood out as particularly critical, as water was essential for the survival of humans and integral to daily life. Food production, domestic use, drinking water, and industrial processes all depended heavily on water [1]. The increased discharge of toxic pollutants into natural water bodies from industries including agricultural, pharmaceutical, food, and mining sectors, severely affected both human and ecosystem health. Water pollution caused deaths and diseases globally, with an estimated 14,000 people dying daily as a result [2].

Additional consequences included sewage and fertilizer runoff, which led to excessive algal growth (algal blooms) that covered large water surfaces, depleted dissolved oxygen levels, and killed aquatic organisms such as fish. Agrochemical contaminants also entered the human food chain through polluted water, resulting in biomagnification. Furthermore, elevated water temperatures reduced oxygen levels, disrupted reproductive cycles, and altered respiratory, digestive, and other physiological functions of aquatic life [3]. If left untreated, these issues would continue to accumulate and pose long-term risks to future generations.

In response, environmental remediation emerged as a solution—aimed at removing or treating hazardous pollutants from water sources, soil, and air to safeguard human health and restore ecological balance [4]. To address these challenges, researchers continuously developed and refined environmental solutions, including the use of nanocomposites.

Nanocomposites were defined as multiphase materials in which at least one phase had dimensions smaller than 100 nm [5]. These complex materials combined two or more components at the nanoscale to exhibit enhanced and often unique properties [6]. They were classified into several types: ceramic-matrix nanocomposites, metal-matrix nanocomposites, polymer-matrix nanocomposites, magnetic nanocomposites, and heat-resistant nanocomposites. Each category had specific applications across diverse fields including air purification, heavy metal removal from wastewater, soil improvement, fertilizer delivery, food packaging, and flame retardancy [7].

Nanocomposites proved to be a promising approach for environmental remediation, offering a greener, more energy-efficient, and cost-effective means of removing toxic metals and other pollutants from wastewater [8–10]. The present article systematically reviewed the mechanisms, benefits, and limitations of nanocomposites such as electrospun nanofibers and polymer/magnetic nanocomposites, for water pollution remediation. This included the removal of heavy metals, organic pollutants, and pathogens. Drawing on peer-reviewed literature from 2010 to 2024, the review focused on material advancements (MXenes, nature-inspired nanocomposites) and persistent challenges (scalability, fouling, regulatory barriers), with the aim of bridging the gap between fundamental research and real-world water treatment applications, thereby laying a scientific and practical foundation for sustainable water processing.

## 2. Fate of Water Pollutants

**Water pollution sources** were classified as either point or non-point. The former referred to pollutants discharged from a single, identifiable source, such as industrial emissions into water bodies, while the latter described pollutants originating from multiple diffuse sources. Industrial waste, mining activities, sewage and wastewater, pesticides and chemical fertilizers, energy production, radioactive waste, and urban development were among the major contributors to water pollution [12].

*2.1.Heavy metals.*

One of the most prominent water pollutants was heavy metals, which included copper (Cu), cadmium (Cd), zinc (Zn), lead (Pb), mercury (Hg), arsenic (As), silver (Ag), chromium (Cr), iron (Fe), and platinum (Pt) [12]. These were inorganic pollutants known for their detrimental health effects on humans and their ability to harm ecosystems. Heavy metals originated from both point and non-point sources and were released into water bodies through industrial activities, mining operations, and agricultural runoff [11]. Since heavy metals were not biodegradable, they tended to bioaccumulate in living organisms over time [11]. Their persistence also led to biomagnification throughout the food chain, impacting all levels of organisms [13]. Most heavy metal ions were toxic or carcinogenic [14], and even at trace levels, they could cause damage to organs such as the lungs, kidneys, liver, prostate, esophagus, stomach, and skin. They were also associated with neurodegenerative diseases and other serious health conditions [15].

*2.2.Organic compounds.*

Another major group of water pollutants was organic compounds, which were divided into two types: biodegradable compounds that required oxygen and could be broken down by bacterial activity, and non-biodegradable compounds that persisted in the environment [16]. Pesticides, herbicides, industrial solvents, and petroleum hydrocarbons were all organic pollutants that entered water bodies through agricultural runoff, improper waste disposal, and industrial discharges. Although these substances were often essential for industrial processes, they were hazardous to human health. Prolonged exposure to organic compounds caused respiratory issues, skin irritation, and in severe cases, life-threatening illnesses such as cancer or neurological disorders [16, 17]. A significant subgroup of organic pollutants was dyes, primarily used in the textile, leather, and paper industries. Inadequate wastewater treatment and disposal practices led to the release of dye pollutants into water streams. These dyes altered the color and clarity of water, reduced light penetration, and disrupted aquatic ecosystems. The resulting decrease in dissolved oxygen levels could lead to hypoxic zones, which were fatal to fish and other oxygen-dependent organisms [18]. Reduced light also inhibited photosynthesis in aquatic plants and phytoplankton, thereby impacting the entire aquatic food chain [19].

*2.3.Nitrates, nitrites and phosphorus.*

Nutrient pollutants such as nitrates, nitrites, and phosphorus compounds primarily originated from agricultural runoff and the overuse of fertilizers [20]. When these nutrients entered water bodies, they elevated nitrate levels in drinking water, leading to methemoglobinemia, or "blue baby syndrome," which was especially dangerous for infants [21]. Additionally, they contributed to algal blooms and high fish mortality, adversely affecting aquaculture, food security, and rural livelihoods in many developing countries [20].

*2.4.Pathogens caused by pollutants.*

Poor sewage treatment, runoff from contaminated surfaces, and human and animal waste introduced pathogens such as bacteria, viruses, and protozoa, into water systems. These microorganisms caused gastrointestinal disorders, including diarrhea and stomach pain, as well as more severe infections that could be fatal [22]. Furthermore, nitrogen oxides, sulfur oxides, and other acidic compounds released by coal-burning power plants, mines, and smelting facilities reacted with water to form acidic pollutants. These acidic waters contaminated drinking water supplies and posed serious health risks [23].

*2.5.Law and regulation for water pollution.*

Several laws and regulations were implemented to mitigate water pollution, including the Environmental Quality (Sewage and Industrial Effluents) Regulations 1979, the Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977 and its 1982 amendments, and the Environmental Quality (Prescribed Premises) (Raw Materials) Regulations 1978 with amendments in 1981. These regulations aimed to reduce industrial emissions and prevent the deterioration of water quality (Department of Environment – Ministry of Environment and Water, n.d.). In addition to regulatory measures, science-based technologies were required to treat existing pollutants after minimizing emissions at their source..

## 3. Mechanism of Technologies

Table 1 presents the summary of key nanocomposite types, their functional mechanisms, advantages, and representative applications in pollutant removal, with further details provided in the following section.

**Table 1.** Mechanisms of nanocomposite technologies for water remediation.

| Nanocomposite Type | Mechanism of Action | Key Advantages | Example Applications | Reference |
|---|---|---|---|---|
| Electrospun Nanofibrous Membranes (ENMs) | High porosity & interconnected pores adsorb/block pollutants via size exclusion & electrostatic interactions | High permeability, low energy use, fouling-resistant | Heavy metal removal (e.g., $Cu^{2+}$ using ZVI-coated nanofibers) | [24] |
| Polymer Nanocomposites | Functional groups (-COOH, -$NH_2$) bind pollutants via chemisorption/photocatalysis | High surface area, tunable hydrophilicity, antimicrobial properties | Dye degradation, microbial growth prevention | [25] |
| Magnetic Nanocomposites | Magnetic cores enable easy separation; polymer shells adsorb contaminants | Reusable, rapid retrieval under magnetic fields, cost-effective | Industrial wastewater treatment | [25] |
| Natural Nanocomposites | Biodegradable materials (sawdust) functionalized with nanoparticles for adsorption | Eco-friendly, low-cost, derived from waste | Dye and heavy metal adsorption | [26] |

*3.1. Nanocomposites.*

As mentioned in the introduction, nanocomposites were defined as materials that combined two or more specific components at the nanoscale to achieve unique and enhanced properties. This enabled the creation of a wide variety of nanocomposites tailored for specific uses and characteristics. Nanocomposites were frequently used in combination with other materials for environmental remediation. One such example was ENMs, which featured high porosity and a linked porous structure, with pores several times larger than the fiber diameter [27]. Increased porosity allowed for greater permeability to fluid streams, and the interconnected pores exhibited enhanced resistance to fouling. These features resulted in lower energy consumption. Furthermore, the nanofibrous membranes' adsorptive capacity and selectivity were enhanced by their small pore size, large accessible surface area, and flexibility in surface functionality and design [28].

### *3.2. Nanocomposite with electrospun nanofibrous membrane.*

A nanocomposite electrospun nanofibrous membrane was developed using polyacrylic or polyvinyl alcohol nanofibers incorporated with multi-walled carbon nanotubes [24]. The surface of the nanocomposite nanofibers was then coated with ZVI nanoparticles. While the multi-walled carbon nanotubes improved the mechanical stability of the nanofibers, the ZVI nanoparticles were used to interact with and remove $Cu^{2+}$ ions from water. According to the findings, $Cu^{2+}$ chemisorption occurred through the chemical reduction of the ions followed by deposition on the ZVI nanoparticles' surface. Due to their large specific surface area, the uniformly dispersed ZVI nanoparticles in the nanocomposite ENM effectively collected copper ions. As a result, this nanocomposite membrane showed great potential for heavy metal ion removal and efficient water treatment. Characterized by nanoscale pores and a substantial surface area, these properties were essential for effective filtration, making the nanocomposite suitable for nanoparticle removal. The small size of the nanofibers and the interconnected pore network allowed the membrane to physically block and trap nanoparticles. A size-based filtration mechanism selectively permitted water molecules to pass through while preventing nanoparticles from doing so, confirming the membrane's efficiency in targeted filtration. Additionally, electrostatic forces attracted charged nanoparticles to the electrospun carbon nanofiber nanocomposite membrane, further enhancing its retention capacity and making it an effective tool for nanoparticle capture [29, 30].

### *3.3. Nanocomposite membranes.*

Nanocomposite membranes also attracted significant attention for wastewater treatment due to their potential to address the dual challenge of water permeability and pollutant rejection or removal, along with their anti-fouling properties. Adsorption, in particular, was a widely used method due to its low cost, simplicity, and operational ease in removing diverse organic and inorganic pollutants from contaminated water. It was a straightforward process wherein the adsorbent's surface played a key role in pollutant removal. Depending on the nature of the pollutant (adsorbate) and the adsorbent, the interaction could be either physical (via weak forces like Van der Waals) or chemical (via strong ionic, metallic, or covalent bonds). An ideal adsorbent exhibited characteristics such as a large surface area, low cost, high adsorption capacity, compatibility, economic feasibility, ease of regeneration, and high selectivity towards water contaminants [26].

### *3.4. Polymer nanocomposites.*

Polymer nanocomposites were introduced as a promising category of adsorbents and photocatalysts due to their high porosity and surface area. These materials could adsorb and degrade pollutants thanks to their strong binding affinity and chemical and thermal stability [25]. To meet specific water treatment needs, structural and physicochemical characteristics—

such as hydrophilicity, porosity, and thermal stability—were tailored, and specific functionalities—such as antibacterial, photocatalytic, or adsorptive capabilities—were integrated [25]. Some polymer nanocomposites interacted with microorganisms in the water; their surfaces either inhibited microbial growth or disrupted pathogen cellular structures. This mechanism contributed to the control of microbiological contamination, thereby improving the water treatment process [10].

*3.5. Natural nanocomposites.*

Natural materials and their derivatives also proved advantageous for pollutant adsorption due to their low cost, sustainability, and effectiveness. As biodegradable and non-toxic substances, various organic waste materials were identified and repurposed into suitable adsorbents for water purification. The integration of nanomaterials with natural substances to form natural nanocomposites was considered beneficial due to the overall combined advantages [26]. For instance, sawdust (SD), a wood-based solid waste, was a low-cost, readily available, and biodegradable material. SD could be easily coated with various conducting polymers through surface polymerization, enabling it to effectively remove dyes and heavy metal ions from contaminated water.

*3.6. Magnetic nanocomposites.*

Other inorganic materials included polymers and metal oxides. Due to their high efficiency, ease of operation, and economic feasibility, polymer or magnetic nanocomposites were also considered advantageous for water purification. Magnetic adsorbents with magnetic cores exhibited strong magnetic properties, while the polymeric matrix provided functional groups suitable for various applications, including water filtration. To synthesize metal oxides based on conducting polymers and their derivatives, chemical oxidation and in-situ polymerization processes were commonly employed. Incorporating metal oxide nanoparticles into polymers increased the surface area-to-volume ratio, thereby enhancing adsorption capacity. Additionally, the presence of carboxyl (-COOH) and amine ($-NH_2$) functional groups in the polymer's repeating units facilitated a complexation process between heavy metal ions or dyes and the metal oxide–polymer nanocomposites [27]. Although magnetic nanoparticles offered the advantage of easy separation from aqueous solutions, they exhibited poor adsorption capacity due to limited functional groups and a tendency to aggregate. To overcome these limitations, magnetic nanoparticles were coupled with conductive polymers, resulting in enhanced stability and adsorption performance [31].

*3.7. Mxene-supported nanocomposites.*

MXenes represented a class of two-dimensional early transition metal carbides or nitrides with the general formula Mn+1XnTx, where M denoted a transition metal (such as Ti, V, Nb), X was either carbon or nitrogen, and Tx referred to surface functional groups (e.g., –OH, –F, –O) [32]. These materials demonstrated considerable success in removing mercury (Hg) ions from water and wastewater when integrated into nanocomposites. In one study, $Ti_3C_2O_x$ MXene, known for its strong multifunctional adsorption capacity, was employed to remove mercury. The combined action of catalytic reduction and adsorption significantly enhanced the mercury removal process. The synthesized MXene-based nanocomposites displayed a wide range of favorable features, including rapid adsorption kinetics, high selectivity and adsorption capacity, excellent recyclability, and effective performance across a broad pH range. Due to these characteristics, the MXene nanocomposite proved to be a superior adsorbent for the rapid adsorption and extraction of mercury from aqueous solutions. Furthermore, it maintained performance for up to five reuse cycles, likely due to its customizable surface chemistry, strong hydrophilicity, and ability to facilitate surface absorption of various contaminants [32].

## 4. Pros and Cons of the Usage of Nanocomposite and Its Future

Table 2 shows the critical evaluation of nanocomposite performance metrics, current challenges, and prioritized research directions for sustainable implementation, with further details provided in the following section.

**Table 2**. Comparative Analysis of Nanocomposite Applications: Advantages, Limitations, and Future Prospects

| Aspect | Pros | Cons | Future Directions |
|---|---|---|---|
| Efficiency | High pollutant selectivity (heavy metals, dyes) | Nanoparticle aggregation reduces effectiveness | Improve dispersion stability (surface modifiers) |
| Sustainability | Low material usage, recyclable (magnetic nanocomposites) | Synthesis may involve toxic chemicals (MXenes) | Develop eco-friendly synthesis routes |
| Cost | Long-term cost savings vs. traditional methods | High initial energy/processing costs (reverse osmosis) | Optimize large-scale production |
| Scalability | Adaptable to diverse pollutants (metals, organics, pathogens) | Biofouling reduces membrane lifespan | Anti-fouling coatings; real-world pilot studies |
| Regulatory | Aligns with stringent water quality standards | Lack of standardized toxicity assessments | Establish safety protocols for nanomaterial release |
| Innovation | Emerging materials (MXenes, bio-based nanocomposites) | Limited long-term environmental impact data | Lifecycle analysis; biodegradable nanocomposites |

### *4.1.Pros of the usage of nanocomposite.*

Selective adsorption was a key characteristic of nanocomposites. These materials could be carefully customized to target specific contaminants within complex mixtures, ensuring efficient and accurate removal. This capability was critical for effectively addressing specific environmental challenges. This was evident in the excellent properties of polymeric nanocomposite membranes, owing to a wide range of operational nanomaterials and structures. These advancements significantly enhanced water and effluent treatment, making polymeric nanocomposite membrane technology more accessible and effective. The distinct behavior of polymeric nanocomposite membranes was attributed to physicochemical characteristics such as mechanical and thermal stability, charge distribution, pore volume, hydrophilicity, and the integration of nanoscale materials [8]. In addition to their selectivity, nanocomposites significantly reduced the environmental burden of cleanup operations. They required less material than traditional approaches, resulting in reduced waste generation, and in some cases, they were recyclable. This was evident in the strong potential of nanocomposite membranes for nanoparticle (NP) filtration from water, primarily due to their tunable pore size, high permeability, and the cost-effective production of nanofibers via electrospinning [30]. Moreover, they offered promising capabilities for the recovery of valuable nanomaterials from complex matrices. This contributed to cost savings and aligned with sustainability goals by reducing the overall environmental impact.

Furthermore, nanocomposites improved the mechanical properties of materials. The incorporation of nanoscale components enhanced the structural integrity of the composite, increasing resilience and enabling performance across a wide range of environmental conditions. This ensured long-term durability in field applications. Another notable advantage of nanocomposites was their adaptability. They could be tailored to treat diverse pollutants, including heavy metals, organic compounds, and pathogens. This versatility enabled their use in a wide range of applications, from contaminated water treatment to soil remediation.

*4.2.Cons of the usage of nanocomposite.*

Although the nanofiltration process using nanocomposite membranes had proven to be successful and efficient at an industrial scale, challenges remained. For example, reverse osmosis, while effective, consumed substantial energy and was therefore primarily applied to water sources that required treatment to meet drinking water standards [8]. Maintaining the uniform dispersion of nanosized molecules in polymer matrices remained a major challenge, as aggregation could significantly affect membrane performance. Aggregation of graphene oxide (GO)–metal oxide nanoparticles on membrane surfaces reduced active surface area, porosity, and overall effectiveness [33, 34]. Another critical limitation in the application of nanocomposite membranes for effluent treatment was biofouling. Biologically derived pollutants could block membrane pores, resulting in significant performance deterioration [35]. Additionally, biofouling increased operational and maintenance costs, ultimately shortening membrane lifespan. Microbial growth and biofilm formation were among the primary factors reducing water flow through nanoporous membranes, thereby increasing energy demand [26]. More research on reverse osmosis was required to reduce operational costs and enhance its broader utilization. If these limitations were addressed, membrane technology could emerge as a viable alternative for pollutant removal in the coming years [8].

Despite the successful use of conducting polymers in nanocomposites, several constraints needed to be addressed, including low electrical conductivity and poor solvent solubility. Moreover, nanoparticles often exhibited instability and agglomeration due to Van der Waals forces and other interactions during synthesis. Therefore, synthesis procedures that ensured maximum nanoparticle dispersion were necessary. In the case of MXene-based nanocomposites, the recovery of 2D nanoparticles from aqueous systems post-adsorption was particularly challenging. Inadequate separation could lead to secondary contamination. Improvements could include replacing hazardous chemicals used in MXene production with more eco-friendly alternatives. Furthermore, enhancing the morphological characteristics of nanocomposites with specific shapes and tailored properties would improve the adsorptive removal of organic pollutants and heavy metals [32]. Recent advances in polymer nanocomposites also raised concerns about potential extreme environmental consequences. A significant issue was the difficulty of removing graphene-based nanocomposites from waste, due to their toxic properties and the risk of fire outbreaks caused by their high thermal conductivity and fire retardancy. The unknown toxicological impacts of nanomaterials added further complexity. Thus, developing standardized methodologies for toxicity assessment was crucial to ensuring safe and practical applications.

Although the water treatment performance of various polymer nanocomposites had been evaluated and compared, it remained difficult to correlate the efficacy of different nanoparticles and identify optimal candidates for long-term use. As such, researchers should focus on developing performance assessment tools that evaluate polymer nanocomposites for practical and commercial deployment [36, 37]. Additionally, understanding the morphology of adsorbents before and after pollutant interaction, along with specific pollutant–substrate interactions, was necessary to improve practical application. Many studies were conducted at the batch scale, which often did not represent industrial or field-scale operations. Therefore, greater emphasis should be placed on the reuse and recycling of nanocomposites and the development of low-risk regeneration strategies to reduce environmental and human health impacts [38].

## 5. Conclusion and Future Research Directions

Nanocomposites have shown great promise for the remediation of water pollution, offering effective, selective, and environmentally sustainable approaches for contaminant removal. They presented advantages over conventional treatment technologies due to their tunable properties, large surface areas, and multifunctional behavior. However, certain limitations must still be addressed to fully realize their practical potential. Future research should focus on developing scalable and environmentally friendly nanocomposite solutions. This includes using bio-based or waste-derived materials to reduce production costs and environmental footprints without compromising functionality. Further efforts are needed to prevent material agglomeration and assess long-term performance under real-world conditions. The development of intelligent, responsive materials capable of detecting and responding to specific pollutants would enhance treatment specificity. Hybrid solutions that combine nanocomposites with natural adsorbents—such as biochar or recycled polymers—may offer more sustainable alternatives. Beyond laboratory testing, field validation is essential to evaluate operational viability. Clear regulatory safety guidelines must also be established to facilitate responsible deployment. Additionally, rigorous cost–benefit analyses—accounting for total life-cycle impacts from synthesis to disposal—are necessary to benchmark nanocomposites against traditional alternatives. The ultimate goal is to transform these advanced materials from experimental innovations into accessible, real-world technologies capable of addressing global water challenges. Achieving this requires close collaboration among researchers, engineers, policymakers, and industry partners to bridge the gap between scientific discovery and practical implementation.

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## Author Contribution

All authors contributed equally to the conception, design, data collection, analysis, and writing of the manuscript. All authors have read and approved the final version of the manuscript.

## Competing Interest

All authors declare that there is no conflict of interest of this publication.

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