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Advances in nanomaterial-assisted remediation of heavy metal contaminants

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Abstract
Heavy metal contamination in the environment poses significant risks to ecosystems and human health, necessitating effective remediation strategies. Traditional methods often face limitations in terms of efficiency, cost, and environmental safety. Nanomaterials, due to their unique properties such as high surface area, reactivity, and selectivity, have emerged as a promising alternative for the remediation of heavy metals like lead, mercury, arsenic, and chromium. This review explores the potential of nanomaterials in heavy metal remediation, highlighting types such as metal and metal oxide nanoparticles, carbon-based nanomaterials, and biopolymers. The mechanisms of nanomaterial-assisted remediation, including adsorption, chemical reduction, electrochemical processes, bioremediation, and photocatalysis, are discussed. Moreover, the challenges associated with their toxicity, economic barriers, and environmental fate are examined. Future directions focus on the development of novel nanomaterials through green synthesis and hybrid approaches, integration with biological treatments, and advancements in environmental monitoring for real-time detection of contaminants. Despite the promising applications of nanomaterials in environmental remediation, careful consideration of their long-term effects and sustainability is necessary for their large-scale adoption.

Keywords: Nanomaterials, Heavy Metal Remediation, Environmental Contaminants, Green Synthesis, Environmental Monitoring

Introduction

Heavy metals have been released widely into ecosystems, which has become a serious environmental problem. Soil, water, and air are heavily contaminated with heavy metals and pose ecological and human health risks. Effective remediation strategies need to be implemented because heavy metals originate from industrial activities and agricultural production as well as natural sources (Mishra et al., 2019). The remediation process requires new solutions since traditional methods prove inefficient while also being expensive and dangerous for the environment thus nanomaterials have emerged as potential replacements. The toxic heavy metals Pb, Hg, Cd, As, Cr and others accumulate in the environment where they create significant threats to all ecosystems and public health systems. The presence of these metals occurs in contaminated sites which include industrial zones and agricultural lands and mining areas (Rahman & Singh, 2019). Heavy metals enter their natural and human-made environments as sources for contamination. Heavy metal contamination results primarily from the activities of mining and metal processing and waste disposal industries. Mining operations frequently discharge arsenic and mercury together with other substances into the surrounding soil and water bodies (Candeias et al., 2018). Aggravating the contamination are agricultural practices, which include the use of chemical fertilizers and pesticides, that introduce metals such as cadmium and lead into the soil (Alengebawy et al., 2021). Natural processes such as volcanic eruptions and weathering of rocks also release small amounts of heavy metals into the environment (Cimboláková et al., 2019). Nevertheless, anthropogenic sources are the main sources of heavy metal enrichment in contaminated areas.

The reactivity and degradation resistance of heavy metals make them persist in the environment. They bioaccumulate once they enter ecosystems and are found in plants, animals, and humans. Because this bioaccumulation creates several environmental problems (e.g., reduced biodiversity and impaired ecosystem functions), this accumulation has become investigated as a significant source of marine pollution. Heavy metals like mercury and cadmium are particularly detrimental to aquatic life because they accumulate in fish, which people consume, and can experience neurological damage, kidney dysfunction, and other types of cancer (Garai et al., 2021). Additionally, continued high concentration of heavy metals in the body can result in severe health problems such as developmental delays, heart problems, and organ toxicity in humans.

Heavy metal contamination poses a threat to human health and the environment, and hence, there is a need for effective remediation of heavy metal contamination. Although effective to some extent, traditional remediation methods are subject to several limitations (Li et al., 2019). Chemical precipitation, soil washing, and excavation, however, are often costly and inefficient. Usually, these methods involve large-scale operations that are not only expensive but also time-consuming. For instance, chemical precipitation requires the use of large amounts of chemicals that may lead to secondary contamination or the production of hazardous waste. Similarly, metals that are deeply embedded or bound in the soil matrix may not be removed by soil washing (Liu et al., 2018). The limitations provided indicate the need for other, more efficient and environmentally friendly solutions to heavy metal remediation. Nanotechnology, the manipulation of materials at the nanoscale (typically less than 100 nanometers), offers a promising solution to the challenges of heavy metal remediation. However, nanomaterials exhibit properties that include high surface area, reactivity, and selectivity, which make them an extremely good choice for environmental cleanup .

Engineered nanomaterials have been created to have different physical, chemical, and mechanical properties from their bulk version. Materials tend to be more reactive in 'real life' at the nanoscale (larger surface area, higher adsorption capacity). Due to these properties, they are suitable for use in environmental applications such as heavy metal remediation (Zou et al., 2016). There are many forms of nanomaterials, including nanoparticles, nanotubes, and nanocomposites, which have different advantages for different remediation needs. This technology provides multiple benefits of nanomaterials above traditional remediation methods. Their large surface area to volume ratio functions as an advantage because it enables better heavy metal absorption and interaction. These materials demonstrate high efficiency in removing contaminants from water, soil and air because of their enlarged surface area (Jawed et al., 2020). The nanomaterials become more potent by incorporating specific ligands or coatings that enable them to seek out particular metals including lead, mercury and arsenic among others.
This review assesses the use of nanomaterials for heavy metal contaminated environment remediation. It evaluates the advantages of nanomaterials in environmental remediation by comparing them to standard practice based on operational costs and reaction schedules and environmental impact. This review investigates both the binding mechanisms of heavy metals with nanomaterials and the major obstacles and possible solutions for extensive environmental cleanup using nanomaterials.

Types of Nanomaterials Used in Heavy Metal Remediation

Nanomaterials demonstrate three distinct features that consist of large surface area and chemical reactivity and molecular-level interaction abilities to serve as essential environmental cleanup tools. Different nanomaterial types serve the remediation of heavy metals through specific mechanisms and advantages that support their environmental applications (Cai et al., 2019). The following section analyzes three fundamental nanomaterial groups composed of metal and metal oxide nanoparticles and carbon-based nanomaterials and biopolymers/bio-based nanomaterials.

Metal and Metal Oxide Nanoparticles

Zero-Valent Iron (ZVI)

Fe^0 nanoparticles serve as one of the primary metal-based nanomaterials which has characteristic role of enhancing reactivity through reduction–oxidation (redox) processes to perform environmental cleanup (Xiao Zhao et al., 2016). ZVI nanoparticles show efficient reducing characteristics that convert dangerous Cr(VI) and arsenic ions into harmless Cr(III) and arsenic (III) compounds. Through reduction-based reactions the nanoparticles perform in situ environmental remediation of soil and groundwater systems by converting toxic metals into non-harmful compounds (Bashir et al., 2022).

Titanium Dioxide (TiO2)

Titanium dioxide nanoparticles exhibit photocatalytic. When exposed to UV light TiO2 nanoparticles decompose organic pollutants alongside eliminating heavy metals including lead, cadmium and mercury from the environment. The use of TiO2 nanoparticles in water treatment shows advantages because they transform dangerous metals into harmless substances (Elmehasseb et al., 2020). The combination of stability and non-toxicity properties in TiO2 nanoparticles makes them suitable candidates for sustainable remediation strategies.

Carbon-Based Nanomaterials

Graphene

The field of environmental remediation demonstrates potential for broad-scale implementation of graphene because it consists of a single carbon layer structured in two-dimensional arrangement. The combination of exceptionally high surface area and electrical conductive properties gives graphene exceptional ability to extract heavy metal ions from contaminated water and soil. Graphene oxide (GO) surfaces with oxygen functional groups enhance its binding capacity to heavy metals while also increasing its hydrophilic characteristics for cadmium, lead and arsenic removal (Subrajit Bosu et al., 2022). The combination of high loading capacity and selective properties derived from large surface area properties in graphene-based materials makes them ideal for treating waste water operations. The remediation process becomes targeted by specific functionalized graphene modifications that enhance its ability to bind particular metal ions (Kong et al., 2021).

Carbon Nanotubes (CNTs)

The potential of carbon nanotubes in heavy metal remediation appears promising because they possess robust mechanical capabilities and good electrical properties alongside their vast surface area (Yu et al., 2018). Carbon nanotubes exhibit an effective mechanism for heavy metal adsorption which includes the removal of lead and mercury alongside copper and chromium. Heavy metal adsorption capacity enhances because carbon nanotubes exhibit both extensive surface area and strong hydrogen bonding and π-π interactions with metal ions. The selective removal of particular metal ions becomes possible through CNT surface modifications because these nanomaterials exhibit high versatility. The specific application of metal removal from polluted water sources by CNTs demonstrates their highest value (Bassyouni et al., 2020).

Biopolymers and Bio-Based Nanomaterials

Chitosan

The biopolymer chitosan develops from crustacean exoskeletons containing chitin which exists within shrimp and crab shells. Use of the naturally occurring substance chitosan represents an environmentally friendly method for heavy metal removal because it occurs naturally and breaks down swiftly without causing toxicity concerns (Zhang et al., 2021). The heavy metals lead, copper and cadmium can be effectively bound by chitosan nanoparticles through their surface groups which contain amino and hydroxyl functional groups. The various functional groups found on chitosan surfaces enable effective heavy metal extraction from water through their ability to generate binding sites for metal ions. The biodegradable nature of chitosan nanoparticles allows for straightforward modification to improve absorption properties thus making them ideal materials for sustainable cleanup operations (Benetteyeb et al., 2023).

Nanocellulose

The nanomaterial nanocellulose originates from cellulose which occurs as a polysaccharide within plant cell walls to serve as an effective bio-based material for environmental remediation. Nanocellulose exhibits advantageous characteristics such as high surface area and biocompatibility together with affordable renewable resource origin which makes it promising for industrial manufacturing. The surface adsorption of heavy metals such as lead, chromium, and mercury on nanocellulose occurs effectively because of its hydroxyl groups as reported by Reshmy et al. (2022). Nanocellulose achieves better heavy metal removal capabilities when functionalized with nanoparticles or polymers. Nanocellulose functions as a sustainable heavy metal treatment material because its natural breakdown does not produce lasting environmental contamination according to Table 1 (Norrrahim et al., 2021).

Table 1: Types of Nanomaterials Used in Heavy Metal Remediation

Nanomaterial Type	Properties/Mechanism	Applications	References
Zero-Valent Iron (ZVI)	Reductive properties; reduces hexavalent chromium (Cr (VI)) and arsenic to less toxic forms	In situ remediation of groundwater and soil; chemical reduction of toxic metals	Xiao Zhao 2016; Bashir et al., 2022
Titanium Dioxide (TiO2)	Photocatalytic properties; degrades organic pollutants and removes heavy metals	Water treatment; oxidative transformation of toxic metals into non-toxic forms	Elmehasseb et al., 2020
Graphene	High surface area; excellent adsorption capacity for heavy metals like cadmium, lead, and arsenic	Water and soil treatment; targeted adsorption of specific heavy metals	Subrajit Bosu et al. 2022; Kong et al., 2021
Carbon Nanotubes (CNTs)	High surface area and mechanical properties; adsorbs heavy metals like lead, mercury, copper, and chromium	Water treatment; selective removal of particular metal ions	Yu et al., 2018; Bassyouni et al., 2020
Chitosan	Environmentally friendly, biodegradable; adsorbs heavy metals like lead, copper, and cadmium	Heavy metal remediation in aqueous solutions; sustainable and biodegradable	Zhang et al., 2021; Benetteyeb et al., 2023
Nanocellulose	High surface area, biocompatible; adsorbs heavy metals like lead, chromium, and mercury	Heavy metal remediation in water; biocompatible and biodegradable	Reshmy et al., 2022; Norrrahim et al., 2021

Properties of Nanomaterials

The remediation of heavy metals through nanomaterials becomes possible because nanomaterials exhibit specific properties including high surface area, high reactivity, adsorption capacity and ion selectivity.

High Surface Area

Nanomaterials present an elevated surface area to their total volume ratio. Such nanomaterials (specifically nanoparticles) exhibit a surface area that surpasses the dimensions of their bulk counterparts thus creating additional active sites where contaminants can interact (Asha & Narain, 2020). A single gram of carbon nanotubes or graphene nanomaterials provides surface area dimensions equivalent to hundreds of square meters. The greater surface area of nanomaterials enables them to efficiently remove contaminants from the environment because they can absorb more heavy metals. The high surface area of nanomaterials enables efficient metal removal from water sources when applied to water treatment (Roy et al., 2021).

High Reactivity and Adsorption Capacity

Nanomaterials exhibit enhanced reactivity because they possess both small dimensions as well as elevated surface energy compared to bulk materials. Nanomaterials display enhanced reactivity because of which they can effectively interact with contaminants and eliminate them rapidly and efficiently (Xu et al., 2018). Zerovalent iron nanoparticles as well as metal and metal oxide nanoparticles perform reduction reactions to convert toxic metal ions like chromium (Cr(VI)) into less dangerous forms (Cr(III)). Heavy metal ions bind easily to nanomaterials based on carbon through their numerous surface functional groups such as carboxyl and hydroxyl groups (Yang et al., 2019). The functional groups present on nanomaterials enhance their adsorption capacity so they can effectively extract heavy metals from polluted environments.

Selectivity and Specificity for Certain Metals

Nanomaterials can be engineered with selective and specific bindings toward particular heavy metals. It is very important that this selectivity is possible with multiple contaminants in real world applications. Functionalization of the nanomaterials with specific ligands or surface coatings can enhance specificity of interaction, affinity, and binding strength for nanoparticles to metal ions. The remediation of lead ions occurs through functionalized graphene oxide while nanocellulose functions specifically for chromium extraction (Reshmy et al., 2022). The targeted remediation technique boosts the efficiency of the process while keeping non-target metals undisturbed and lowering treatment expenses as Figure 1 illustrates. The removal of multiple types of contaminants becomes simpler with nanomaterials in complex contamination scenarios (Liaquat et al., 2022).

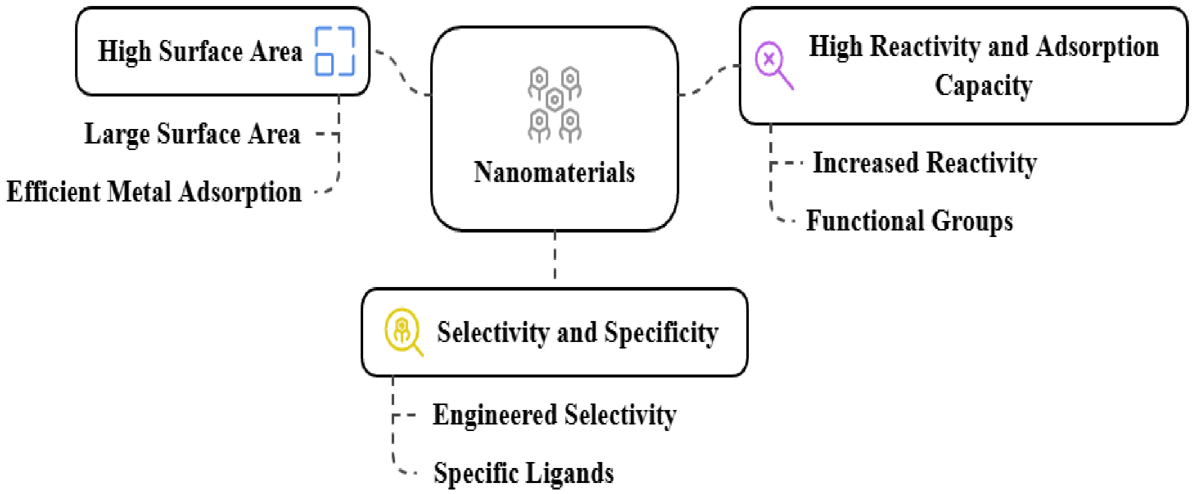

Figure 1: Key Properties of Nanomaterials for Heavy Metal Remediation

Mechanisms of Nanomaterial-Assisted Remediation

Adsorption and Absorption

Nanomaterials utilize adsorption and absorption as essential methods to remove heavy metals from the environment. Heavy metal ions interact with nanomaterials through this process to achieve contaminant removal or immobilization in the environment. Adsorption refers to the adhesion of metal ions onto the surface of nanomaterials (Sarma et al., 2019). Nanomaterials function as effective metal ion adsorbents because they have large surface areas alongside multiple functional groups. TiO2 and iron oxide metal oxide nanoparticles remove arsenic, cadmium and lead metal ions through their surface hydroxyl groups (Qumar et al., 2022). The large surface area of carbon nanomaterials including graphene and carbon nanotubes acts as one of the key factors contributing to high adsorption processes. Heavy metals can be successfully extracted from polluted areas by graphene oxide because of its functional groups including carboxyl and hydroxyl groups.

The structure of nanomaterials permits metal ions to penetrate through electrostatic interactions and ion exchange processes or complexation with specific binding sites (Singh et al., 2021). Nanomaterials based on chitosan and nanocellulose exhibit metal chelation capability due to their surface-bound functional groups which enable heavy metal absorption. Nanomaterials use their dual adsorption and absorption capabilities to extract metal ions from extensive contaminated water and soil volumes (Rajendran et al., 2022).

Chemical Reduction

The remediation process through nanomaterials depends heavily on chemical reduction for treating dangerous metal ions such as hexavalent chromium (Cr(VI)) and arsenic (As(V)) which have established carcinogenic properties. Zero-valent iron nanoparticles (ZVI) serve as a common remediation agent because of their powerful reducing capabilities. ZVI nanoparticles function as electron donors to decrease metal ions from toxic high oxidation states into more stable and less harmful forms (Pasinszki & Krebsz, 2020). Zero valent iron particles perform Cr(VI) pollution reduction in industry by converting this harmful substance into Cr(III) which exhibits lower toxicity and mobility. ZVI nanoparticles reduce Cr(VI) by transferring electrons from the nanoparticles to Cr(VI) ions which results in the formation of immobile Cr(III) that has limited water solubility. Various nanomaterials demonstrate the ability to transform arsenic and uranium as well as other metal ions into less dangerous oxidation states (Tolkou et al., 2020).

Electrochemical Processes

The application of nanomaterials extends to electrochemical procedures that extract metals from solutions. Electrochemical reduction serves as an exceptionally strong technique to process contaminated water and soils through metal ion reduction with electrical current application. Electrochemical reactions benefit from nanomaterials because they improve both operational efficiency and the selectivity of reduction reactions. The removal of heavy metals including copper and cadmium and lead occurs through electrochemical systems which utilize nanoparticles like gold silver and platinum as electrodes (Maarof et al., 2017). The nanoparticles maintain a small dimension and extensive surface exposure that promotes effective electron transfer for metal ion reduction. The electrodes in electrochemical cells undergo research using carbon-based nanomaterials including graphene and carbon nanotubes. The electrochemical process efficiency benefits significantly from these nanostructures due to their high conductivity and large surface area and adjustable surface properties (Xie et al., 2019). Electrodes made from nanomaterials enable Pb(II) reduction to Pb(0) while simultaneously removing the solid Pb(0) from solution. The electrochemical reduction shows promising results for metal ion reduction but its traditional methods may not reach complete efficiency (Waheed et al., 2018).

Bioremediation with Nanomaterials

Bioremediation refers to microorganisms natural process of the breakdown or transformation of pollutants. Microbial cultures can be used as nanomaterials nanocarriers to improve their performance in metal contaminated environments. For example, functionalized nanoparticles can be utilized to deliver nutrients, or enzymes that will improve the odds of the microorganisms being able to metabolize and degrade the chemicals. Additionally, nanomaterials possess a large surface area for attaching beneficial microorganisms like bacteria with specialisation in heavy metal detoxification (Iravani & Varma, 2020). The biotransformation of metals can also be enhanced by nanomaterial-facilitated microbial interactions. For example, bacteria interact with metal oxide nanoparticles and reduce toxic metal such as Cr (VI) to Cr (III), or methylate mercury so that it becomes less toxic. Additionally, some nanochitosans, for example, prepared by malic acid and chitosan, are capable of adsorbing heavy metal like Copper (C. Zareie 2013). The interaction between nanomaterials and microbial processes is of special value for the remediation of complex contamination sites with many metals present, and conventional methods may not be as effective.

Photocatalysis and Photoreduction

In photocatalysis and photoreduction, nanomaterials are also effective since light is used to perform chemical reactions in order to degrade contaminants or reduce metal ions. Nanomaterials are used in which photocatalysis refers to the breakdown of organic pollutants and the reduction of heavy metals under light, with ultraviolet (UV) or visible light. They are one of the most widely studied photocatalytic nanomaterials, and are TiO2. The TiO2 nanoparticles will generate highly reactive hydroxyl radicals and superoxide anions under UV light, which can degrade organic pollutants and reduce heavy metal ions (Nasr et al., 2018). Thus, TiO2 has been demonstrated to reduce Cr(VI) to Cr(III) and break down organic pollutants (e.g., pesticides, dyes). Because TiO2 nanoparticles are highly photocatalytically active, they can be used for water and air purification applications where they can simultaneously remove organic contaminants and heavy metals. TiO2 or graphene based composites can be used as photo reducing agent to reduce metal ions under light (Purabgola et al., 2022). Upon light, these materials emit reactive species, which then reduce heavy metal ions (mercury or arsenic) to their less toxic forms. In particular, the photoreduction is well suited for treating contaminated water since it can simultaneously remove organic contaminants and reduce metal ions, making it an effective dual purpose remediation strategy as depicted in Table 2.

Table 2: Mechanisms of Nanomaterial-Assisted Heavy Metal Remediation: Key Processes and Nanomaterials Used

Mechanism	Description	Nanomaterials Used	References
Adsorption and Absorption	Adsorption is the adhesion of metal ions to the surface, while absorption involves penetration into the nanomaterial structure.	Metal oxides (TiO2, iron oxide), Carbon-based nanomaterials (graphene, CNTs), Biopolymers (chitosan, nanocellulose)	Sarma et al., 2019; Qumar et al., 2022; Singh et al., 2021; Rajendran et al., 2022

Chemical Reduction	Nanomaterials like Zero-Valent Iron (ZVI) reduce toxic metal ions like Cr(VI) and arsenic to stable, non-toxic forms.	Zero-Valent Iron (ZVI), Metal oxide nanoparticles	Pasinszki & Krebsz, 2020; Tolkou et al., 2020
Electrochemical Processes	Metal ion reduction via electric current, enhanced by nanomaterials like gold, silver, and carbon nanotubes for better efficiency.	Gold, silver, platinum nanoparticles, Graphene, Carbon nanotubes	Maarof et al., 2017; Xie et al., 2019; Waheed et al., 2018
Bioremediation with Nanomaterials	Nanomaterials enhance microbial activity and metal bioavailability, aiding pollutant breakdown.	Nanocellulose, Chitosan, Functionalized nanoparticles	Iravani & Varma, 2020;
Photocatalysis and Photoreduction	Nanomaterials like TiO2 use light to degrade organic pollutants and reduce heavy metals.	Titanium dioxide (TiO2), Graphene-based composites	Nasr et al., 2018; Purabgola et al., 2022

Applications of Nanomaterials in Real-World Remediation

Water Treatment

In recent years, water treatment with nanomaterials has received great attention as an extremely efficient and versatile process for the removal of heavy metals from aqueous solutions. These toxic metals include lead, mercury, arsenic, cadmium and chromium that pollute water bodies and can be harmful to human health and the environment. Nanomaterials having large surface area and high reactivity make them suitable for selective adsorption, reduction and immobilization of these contaminants for water purification (Santhosh et al., 2016). The advantage of using nanomaterials for water treatment is that nanomaterials have the ability to target specific heavy metals. For example, it has been shown that graphene oxide is able to adsorb arsenic (As) and lead (Pb) from contaminated water as graphene oxide surface functional groups (carboxyl and hydroxyls) interact with the metal ions. These techniques provide scalability benefits and minimal environmental impact thus making them suitable for fighting global water pollution.

Soil Remediation

Soil heavy metal contamination occurs frequently in regions that contain heavy industrial zones and mining facilities and agricultural operations. The traditional soil remediation techniques like soil excavation together with soil washing provide high costs while frequently generating additional pollution at the site. The process of enhancing heavy metal immobilization or removal in soil represents a better choice over nanomaterial-based soil remediation because it combines sustainability with affordability. Nanomaterial amendments receive direct application to polluted soils for both contaminant immobilization and removal enhancement. Nanotechnology employs nano iron as a soil contaminant cleaner that removes chromium, lead, mercury and cadmium metals from polluted soils. Heavy metals react with these materials to become less soluble and mobile within the soil environment (Vasarevičius et al., 2019). Nanotubes and graphene oxide among carbon-based nanomaterials show adsorption and retention properties for heavy metals which prevents their continued movement through the environment.

Air Pollution Control

Among the most significant airborne heavy metal pollutants are mercury, cadmium, and lead, which pose health risks through inhalation or deposition onto land and water bodies. The cost and efficiency of traditional air pollution control means of filtration and adsorption are limited, particularly for the removal of fine particulate matter and gases. Heavy metal removal from airborne pollutants is offered by nanomaterials. With great promise in air filtration applications, carbon-based nanomaterials have demonstrated particular promise in carbon nanotubes (CNTs). Being high on surface area and tunable surface properties, they make excellent adsorbents for heavy metal ions and particulate matter from the air. The use of CNTs to capture metal particles, such as mercury, from industrial emissions, one of which is a challenging pollutant due to its gaseous nature. Like graphene oxide, the adsorption capacity of graphene oxide has also been studied as an adsorbent material for the removal of airborne heavy metals, including lead and arsenic, because of its high adsorption capacity and stability. Air purification is also done using Photocatalytic Nanomaterials. One of the most used photoreactors for organic pollutant removal and gaseous heavy metal oxidation is photocatalytic oxidation, owing to titanium dioxide (TiO2) nanoparticles, which degrade organic pollutants and remove gaseous heavy metals, such as mercury and arsenic. TiO2 under UV light produces reactive oxygen species (ROS) that oxidize contaminants and convert them into less toxic forms that can be easily removed from the air (Rafique et al., 2020). The photocatalytic process has been used in air purification systems for the air purification of industrial and urban environments to decrease the levels of inorganic and organic pollutants as shown in Table 3.

Table 3: Applications of Nanomaterials in Remediation: Comparison of Water Treatment, Soil Remediation, and Air Pollution Control

Application	Water Treatment	Soil Remediation	Air Pollution Control	References
Heavy Metals Targeted	As, Pb, Cr(VI), Hg	Cr, Pb, Hg, Cd	Hg, Cd, Pb	Santhosh et al., 2016;
Method	Adsorption, Reduction	Immobilization, Removal	Filtration, Adsorption	Guo Yu et al., 2021; Vasarevičius et al., 2019
Material Used	Graphene Oxide, ZVI, TiO2	Nano-Iron, Carbon Nanomaterials	CNTs, Graphene Oxide, TiO2	Qumar et al., 2022; Rafique et al., 2020
Environmental Impact	Low	Sustainable	Effective	Vasarevičius et al., 2019
Scalability	High	High	High	Rajendran et al., 2022

Challenges and Limitations

Toxicity of Nanomaterials

Although nanomaterials have the potential to resolve environmental remediation issues, they are also highly toxic and have the potential to adversely affect ecosystems as well as human health. Nanomaterials are small in size and highly reactive, and hence, can react with biological systems in unknown ways, which may pose hazards to the environmental uses of these materials.

Nanomaterials that escape the environment tend to accumulate within water bodies and soil as well as sediment deposits. These small-sized particles have the ability to penetrate biological membranes and tissues so they create environmental risks for organisms throughout different trophic levels. The accumulation of silver nanoparticles (AgNPs) in aquatic organisms shows they might cause toxicity damage to entire aquatic food chains (Ranjitha, 2020). The function of aquatic organisms becomes impaired when these particles disrupt enzymes and reproduction rates and growth patterns in aquatic environments. Carbon nanotubes (CNTs) among carbon-based nanomaterials trigger oxidative stress that damages cells of microorganisms and aquatic animals while potentially impacting biodiversity (Freixa et al., 2018). Respiratory issues alongside lung damage occur when people inhale nanomaterials including titanium dioxide (TiO_2) nanoparticles and zinc oxide (ZnO) nanoparticles. Nanomaterials enter the blood circulation by penetrating through skin contact or respiratory absorption before they reach vital organs including the brain and kidneys and liver where they accumulate and potentially create harmful health consequences. For example, exposure to some metal-based nanoparticles can cause neurotoxicity, kidney damage, or inflammation (Wu & Tang, 2018).

Economic and Technical Barriers

Although nanomaterials have great potential for environmental remediation, there are a number of economic and technical barriers preventing their mass implementation. It also includes high production costs, difficulty in scaling up the process, and technical barriers in manufacturing and application. The main obstacle to the wide use of nanomaterials in environmental remediation is that the scaling from laboratory scale to industrial projects is difficult (Saleh, 2022). Process that generates nanomaterials frequently require combinations of complex patterned processes with expensive characterizations, including but not limited to chemical Vapor deposition, sol-gel processing, and high temperature processing. Among other things, such methods may not be economically viable for large-scale production and deployment. For example, to produce graphene and other carbon-based nanomaterials, advanced techniques with high energy are required for the production, driving the cost the per unit of material to be prohibitively high for commercial use. However, these methods will not scale to remediate large contaminated sites without substantial advancement in the production efficiency and cost reduction of these methods. Nanomaterials present a major challenge due to their high production expenses. The production of carbon nanotubes (CNTs) and graphene, along with metal nanoparticles, remains expensive because specialized equipment and synthesis procedures are necessary (Rahman et al., 2019). The high effectiveness of these materials in heavy metal removal from water, soil, and air makes them impractical for large-scale use due to their elevated cost.

Environmental Fate of Nanomaterials

The environmental fate of nanomaterials is an issue of great concern because if long-term and high accumulation of nanomaterials in ecosystems occurs, they can have negative unintended ecological impacts. When nanomaterials are released into the environment either from these industrial applications or through degradation of remediation material, the behavior and impact of these materials over time are not known. This is beneficial for the intended purpose of nanomaterials being used to remove contaminants, as they are often designed to be stable and resistant to degradation in environmental conditions. But at the same time, being stable also may mean they could live for a long time in an ecosystem. One example is that some nanoparticles may accumulate in soil or sediment and interact with soil microorganisms, plants, and animals. This accumulation of nanomaterials in the food chain is possible and could accumulate in higher organisms (A. M. Maharramov et al., 2019). In addition, their size and surface area could promote bioaccumulation and even induce organisms to higher toxicities at low concentrations.

The environmental impact of accumulated nanomaterials is largely unknown in the long term. Some nanomaterials are biodegradable or will decay under environmental conditions, but others do not degrade and may persist with further negative effects. Factors relating to the size, concentration, and type of surface chemistry, as well as other environmental variables (e.g., pH, temperature, organic matter), affect the toxicity and mobility of nanomaterials in the environment. The behavior and fate of these nanomaterials are influenced by these factors, which makes the prediction of these nanomaterials' environmental persistence and impact difficult (Lead et al., 2018). Another concern is that nanomaterials may release contaminants that they have adsorbed or immobilized. For example, the nanomaterials used in water treatment adsorb heavy metals, but if the adsorbed heavy metals eventually degrade or release their contaminants, these heavy metals could return to the environment. If this leaching process takes place, it can undermine the efficiency of nanomaterials used to aid in remediation and could lead to secondary pollution as shown in Figure 2

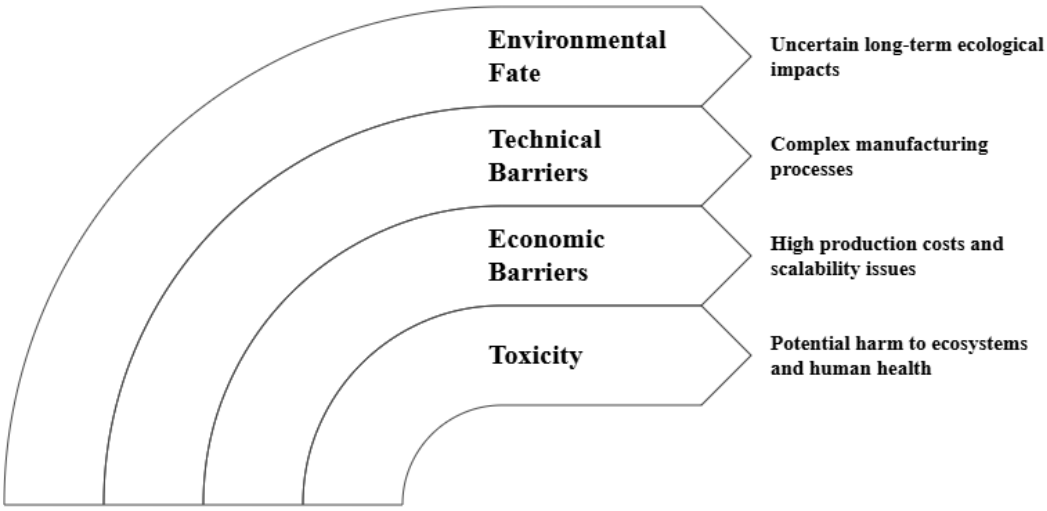

Figure 2: Challenges and Limitations of Nanomaterials in Environmental Remediation

Future Directions and Innovations

Novel nanomaterials with improved properties will play a future role in the development of nanomaterial-based remediation. Green synthesis, which involves environmentally friendly production methods of nanomaterials through their use of plant extracts, fungi, or bacteria is one promising direction. The environmental impact of synthesis processes is minimized by these methods, which might provide biodegradable substitutes for conventional nanomaterials. The other is hybrid nanomaterials, formed from combining the strengths of two or more materials. As an example, carbon-based nanomaterials and metal nanoparticles hybrid materials can provide catalytic performance that is enhanced reactivity, stability, and selectivity for pertinent contaminants. Combined methods are being explored for a more efficient and regarded scope of environmental remediation. The synergistic combination of nanomaterials with biological treatment, such as the use of nanomaterials to improve microbial degradation or metal resistance, provides a potential method to clean contaminated environments. Additionally, the development of smart nanomaterials able to implement in situ remediation with real-time adaptability to the environmental stress (temperature, pH, and concentration of contaminant) is envisaged. They can tune these nanomaterials to selectively target and neutralize particular contaminants so that the remediation can better be achieved with less effort and less cost. Environmental monitoring is also powered by nanomaterials. Real-time detection systems based on nanomaterials will bring significant improvements in the development of the ability to monitor heavy metal contamination in water, soil, and air. Highly sensitive and specific nanomaterial sensing, in terms of nanosensors and nanoparticle-based probes, can detect trace levels of contaminants. In specific terms, these advancements will make it possible to continuously monitor environmental qualities, give early warnings to intervene quickly when threatened. Environmental monitoring systems have valuable intangible benefits that are inherent in preventing pollution and protecting ecosystems, while the integration of nanomaterials into such systems is essential.

Conclusion

Remediation of heavy metals can be effectively achieved using nanomaterials that have many advantages over traditional methods. These properties make them effective in the targeted removal of toxic metals such as lead, mercury, and arsenic in such media as water, soil, and air. There has been good evidence that nanomaterials such as zero valent iron (ZVI), graphene oxide, and titanium dioxide (TiO2) are very good for environmental cleanup and reduce or remove the content (contaminants). Despite these advantages, challenges remain. The toxicity of nanomaterials to ecosystems and human health, along with economic barriers such as high production costs, limits their large-scale adoption. The environmental fate of nanomaterials, particularly their persistence and also their bioaccumulation in ecosystems, is of concern for long-term ecological effects. Ongoing research to determine the safe and sustainably use of nanomaterials in environmental remediation will be required to address these issues. Future moves by going green with green synthesis, hybrid nanomaterials, and more efficient, more sustainable materials should be forthcoming. The integration of nanomaterials with other remediation techniques, especially biological treatment and smart nanomaterials, could provide more cost-effective and flexible options. The bright future of nanomaterials in environmental monitoring is due to their capacity to provide real time detection of contaminants in pollution management.

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