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Review Article

Mechanisms and Effectiveness of Soil Remediation Using Different Available Techniques: A Review

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ABSTRACT

Soil contamination due to heavy metals (HMs) poses a significant environmental and public health challenge. Traditional remediation methods have limitations such as inefficiency, high costs, and secondary pollution. Recent advances in nanotechnology offer promising alternatives through the application of nanoparticles (NPs) for soil remediation. This paper explores the mechanisms and effectiveness of NPs in the remediation of HM-contaminated soils, focusing on various physicochemical and biological processes, and highlights their advantages and potential risks.

Key words: Heavy metals, Metal oxides, Nanoparticles, Plant extract, Soil contamination, Soil remediation.

1. INTRODUCTION

The increasing accumulation of heavy metals (HMs) in soil and their subsequent entry into the food and water supply chains is major environmental concerns [1-5]. HMs such as Hg(II), Cr(V), and Cd(II) are non-biodegradable and highly toxic, making their remediation critical [6-10]. Soil acts as a vital sink for these contaminants, impacting organisms from microbes to humans. Traditional remediation techniques include thermal treatment, filtration, adsorption, chemical abstraction, and microbial degradation [11-14]. However, these methods often suffer from drawbacks such as high costs, inefficiency, and secondary pollution [15-20].

Nanotechnology has emerged as a novel approach to address these challenges, offering enhanced remediation capabilities due to the unique properties of nanoparticles (NPs) [21-24]. NPs, with their high surface area-to-volume ratio and reactive surfaces, provide new dimensions for the remediation of polluted soils [25-32]. This paper discusses the mechanisms by which plants and NPs can remediate HM-contaminated soils, their applications, and potential risks

2. TYPES OF SOIL CONTAMINANTS

2.1. HMs

Lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are common HMs that contaminate soil [33,34].

2.2. Organic Pollutants

Pesticides, polycyclic aromatic hydrocarbons (PAHs), and petroleum hydrocarbons are significant organic contaminants [34,35].

2.3. Other Hazardous Substances

Persistent organic pollutants and emerging contaminants such as pharmaceuticals and personal care products [36-38].

3. NPS IN SOIL REMEDIATION

NPs, due to their high surface area-to-volume ratio and reactivity, are ideal candidates for soil remediation. They interact with contaminants at the molecular level, offering various mechanisms for remediation [39-41].

3.1. Types of NPs Used in Soil Remediation

3.1.1. Nano Zero-valent iron NPs (nZVI)

Extensively used for reducing and immobilizing HMs and degrading organic pollutants due to their high reactivity and cost-effectiveness (Table 1) [42].

3.1.2. Carbon-based NPs

Carbon nanotubes (CNTs) and graphene oxide are effective adsorbents for a wide range of contaminants due to their large surface area and functional groups [43].

3.1.3. Metal oxide NPs

Titanium dioxide (TiO_2), iron oxide (Fe_3O_4), and zinc oxide (ZnO) NPs are used for their catalytic and adsorptive properties [44].

3.1.4. Bimetallic NPs

Combining two metals, such as iron and palladium, enhances reactivity and selectivity for specific contaminants. Bimetallic NPs are effective in degrading chlorinated organic compounds and HMs [45-48].

4. EFFECTIVENESS OF NP-BASED SOIL REMEDIATION

The effectiveness of NP-based soil remediation depends on several factors, including the type of NPs, soil characteristics, contaminant

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properties [49,50], and environmental conditions [51-53]. Studies show high removal efficiencies for various contaminants [54-56]. For instance, nZVI has achieved over 90% removal of HMs such as lead and chromium, whereas TiO_2 NPs have degraded over 80% of organic pollutants under optimal conditions [57-61].

4.1. Mechanisms of NP-Based Remediation

4.1.1. Physicochemical processes

NPs facilitate the removal of contaminants through various physicochemical processes, including adsorption, precipitation, catalysis, and redox reactions [62]. These processes alter the chemical state and mobility of HMs, making them less toxic and more stable (Figure 1) [63-68] .

Table 1: Different plants used for the removal of different heavy metals.

Plant name	Type of phytoremediation	Metal	Mechanism	References
Silene vulgaris	Phytostabilization	Fe, Ni, Cu, Al, Sn, and Zn	Binding with a protein with oxalate oxidase activity in the cell wall; accumulation in the cell wall as silicates	[100]
Sedum alfredii H	Phytostabilization	Pb and Cd	Induction of glutathione biosynthesis that binds metals in roots	[101-104]
Imperata cylindrica, Miscanthus floridulus	Phytostabilization	Cd, Zn, Cu, and Pb	Fibrous root system retaining the metals	[105]
Lupinus albus	Phytostabilization	As and Cd	Metal accumulation in root nodules; increasing the pH in the rhizosphere by citrate release	[106]
Athyrium wardii	Phytostabilization	Cd and Pb	Root retention of metals	[107,108]
Salicornia bigelovii	Phytovolatilization	Se	Volatilization as dimethyl selenide	[109]
Sedum alfredii	Phytoextraction	Pb and Cd	Induction and accumulation of phytochelatin that binds metals in above-ground parts	[104]
Ceratophyllum demersum	Phytoextraction	Cd	Production of phytochelatin for metal binding in shoots; activation of cysteine synthase, glutathione-S-transferase, and glutathione	[110]
Brassica juncea	Phytoextraction	Cd	Synthesis of phytochelatins (PCs), glutathione reductase, non-protein thiols, and glutathione for metal binding in shoots	[111]
Thlaspi caerulescens, Thlaspi ochroleucum	Phytoextraction	Zn, Cd, Cr, Cu, Ni, and Pb	Lowering the pH of the rhizosphere; thus enhancing metal solubilization	[112]
Cynodon dactylon	Phytostabilization	As, Zn, and Pb	Binding with hyphae of mycorrhizae; Release of organic acids	[113]
Pteris vittata	Phytoextraction	As	Increased colonization; exploring more soil	[113]
Thlaspi goesingense	Phytoextraction	Ni	Lowering the soil pH; release of ligands into the rhizosphere	[114,115]
Sedum alfredii	Phytoextraction	Zn	Metals loaded into leaf sections and protoplast	[116]
Arabidopsis halleri	Phytoextraction	Cd and Zn	Accumulation in trichomes and mesophyll cells	[117]
Alyssum species, *Brassica juncea*	Phytoextraction	Ni	Binding of the metals with histidine for detoxification	[118,119]

Table 2: Nanomaterials and uses in soil remediation.

Nanomaterial type	Function	Reference
Nano zero-valent iron (nZVI)	Reduction of heavy metals (e.g., Cr (VI) to Cr (III)); immobilization of contaminants	[120]
Carbon nanotubes (CNTs)	Adsorption of organic and inorganic pollutants	
Titanium dioxide (TiO_2)	Photocatalytic degradation of organic pollutants	
Zinc oxide (ZnO)	Removal of heavy metals through adsorption	
Iron (III) oxide (Fe_3O_4)	Removal of heavy metals; magnetic separation	
Mesoporous silica nanoparticles	Immobilization of contaminants; enhanced adsorption due to high surface area	
Nickel and magnesium oxide (NiO, MgO)	Adsorption of metal ions (e.g., Zn^{2+}, Cu^{2+}, and Cr^{3+})	
Cobalt and cobalt oxide	Photocatalytic degradation under sunlight	
Electrospun nanofibrous webs	Biological degradation of pollutants	
Nanobiosorbents and nanobiosurfactants	Enhanced bioremediation processes by increasing the bioavailability of pollutants	
Nanophytoremediation	Utilization of nanomaterials to enhance plant uptake and detoxification of pollutants	

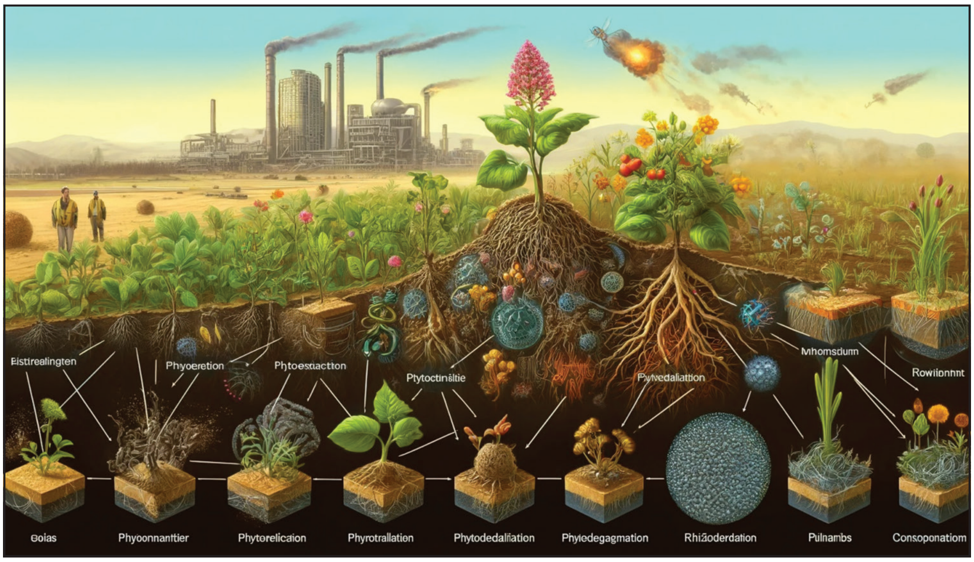

Figure 1: Soil remediation mechanisms using plants and nanoparticles.

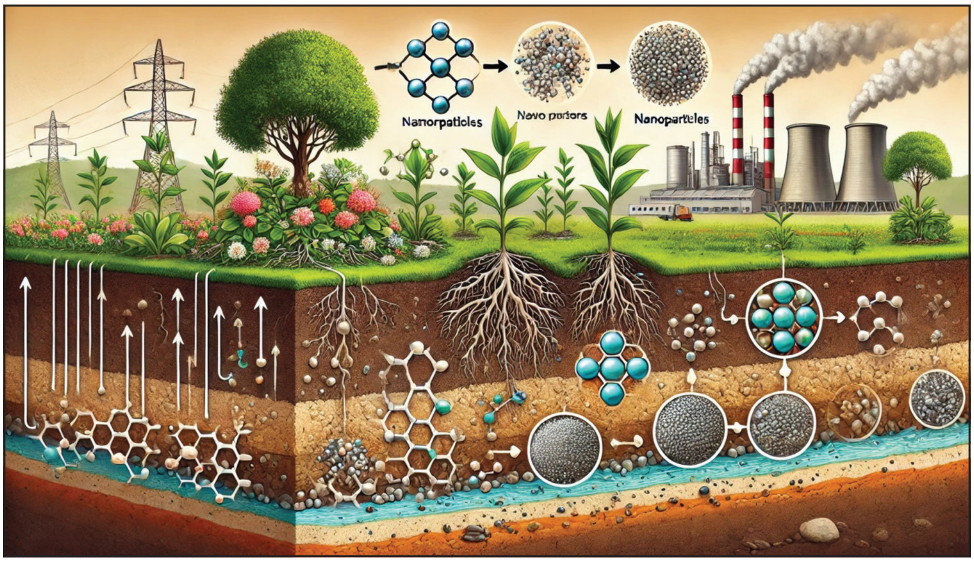

Figure 2: Different layers of soil and removal of contaminants.

4.1.1.1. Adsorption

NPs, particularly those with high specific surface areas such as carbon-based nanomaterials and metal oxides, adsorb HMs from the soil matrix through surface interactions (Figure 2) [69-72].

4.1.1.2. Precipitation

NPs induce the precipitation of HMs as stable compounds, reducing their mobility and bioavailability [73-75].

4.1.1.3. Catalysis

NPs serve as catalysts for redox reactions, transforming toxic HMs into less harmful forms. For example, nZVI reduces Cr(VI) to Cr(III), a less toxic form [76-78].

4.1.1.4. Ion exchange

Certain NPs can exchange ions with HMs in the soil, effectively immobilizing them [79-81].

4.1.2. Biological processes

NPs also enhance bioremediation processes by interacting with soil microbes and plants, promoting the breakdown and uptake of contaminants.

4.1.2.1 Bio stimulation

NPs stimulate microbial activity by providing essential nutrients or enhancing the bioavailability of contaminants, facilitating microbial degradation [82].

4.1.2.2. Bioaccumulation

Plants and microbes can uptake NPs along with adsorbed HMs, reducing the concentration of contaminants in the soil [83].

4.1.2.3. Phytoremediation

NPs enhance plant uptake of HMs through root absorption and translocation. Plants such as hyperaccumulators benefit from the increased availability of HMs due to NP-mediated mobilization (Table 2) [84].

5. APPLICATIONS OF NPS IN SOIL REMEDIATION

5.1. nZVI

nZVI is widely used for its strong reduction capabilities and large surface area. It effectively transforms toxic HMs into less harmful forms. Studies have shown that nZVI, combined with biochar or stabilizers such as carboxymethyl cellulose (CMC), significantly

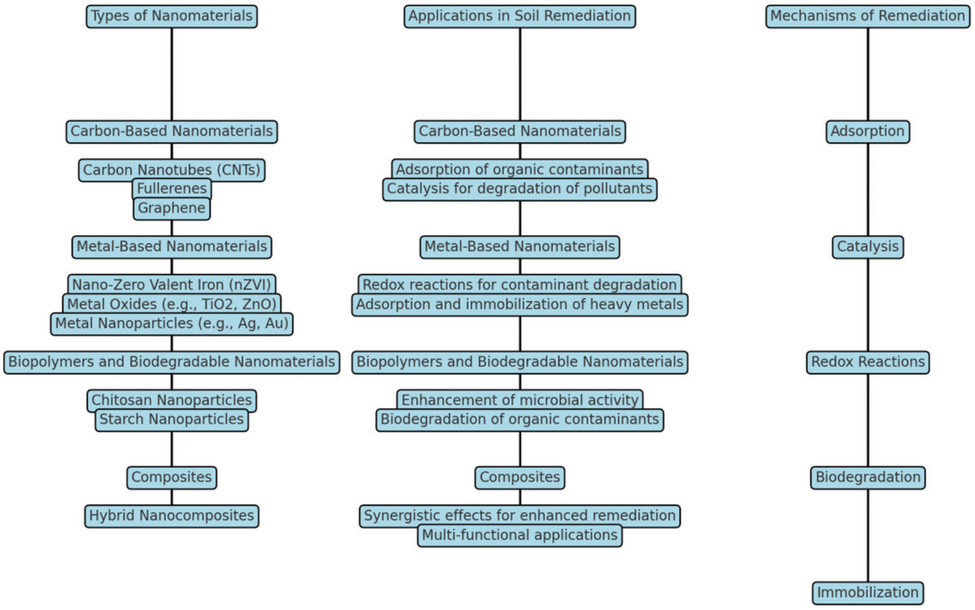

Figure 3: Flow diagram showing types of nano material its applications and mechanism in soil remediation.

Table 3: Different heavy metals and its source in soil contamination.

S. No.	Heavy metals	Sources
1	Cr (VI)	Ferroalloys, mining, the leather industry, and metallurgy, etc.
2	Pb^2	Pesticides, fertilizers, batteries, metal plating, and ore smelting
3	As	Coals, ceramics, metallurgy, animal supplements, electrical production, geochemistry, and pesticides
4	Cd^2	Coal burning, pigments, and metal coating batteries
5	Hg	Industries of metallurgy, catalyst, mercury lamps, paper and pulp, pharmaceuticals, and agriculture
6	Ni^2	Glass batteries, ceramics, and catalyst
7	Cu^2	Water pipelines, metals, and the chemical and pharmaceutical sectors
8	Zn^2	Rubber, paint, PVC stabilizers, zinc alloys, and stabilizers

enhances the removal efficiency of contaminants such as chromium, cadmium, and lead (Figure 3) [85-89].

5.2. Carbon-Based Nanomaterials

CNTs, graphene oxide, and biochar-derived NPs are effective adsorbents for HMs. They offer high surface area and functional groups that facilitate the binding of contaminants, making them stable and less bioavailable [90].

5.3. Metal Oxide NPs

Metal oxides such as titanium dioxide (TiO_2), ZnO, and iron oxides are used for their photocatalytic and adsorption properties. They degrade organic pollutants and adsorb HMs, reducing soil toxicity (Table 3) [91].

6. CASE STUDIES AND PRACTICAL APPLICATIONS

6.1. Reduction of HMs

6.1.1. nZVI for chromium reduction

Zero-valent iron NPs have been effective in reducing Cr(VI) to Cr(III). Studies report up to 98% removal of Cr(VI) in soil within 24 h at a pH level of 5 [92].

6.1.2. Biochar and nZVI

Combining nZVI with biochar enhances the reduction capacity and removal efficiency, with 66% of Cr(VI) removed from the soil [93].

6.2. Degradation of Organic Pollutants

6.2.1. TiO_2 for organic pollutant degradation

Titanium dioxide NPs degrade organic contaminants such as pesticides and PAHs under UV light, achieving over 80% degradation efficiency [94].

6.2.2. Stabilized nZVI for DDT removal

nZVI stabilized with CMC has shown effective removal of organic contaminants like DDT, with 25% removal from the soil within 72 h [95].

6.3. Advantages and Challenges [96]

6.3.1 Advantages

6.3.1.1. High efficiency

NPs offer high removal efficiencies for a wide range of contaminants.

6.3.1.2. Cost-effectiveness

NP-based methods can be more cost-effective than traditional remediation techniques.

6.3.1.3. Environmental friendliness

These methods are environmentally friendly, causing minimal disruption to soil structure and fertility.

6.3.2. Challenges [97]

6.3.2.1. Potential toxicity

The environmental and health impacts of NPs themselves need careful assessment to avoid secondary contamination.

6.3.2.2. Scalability

Large-scale application of NPs for soil remediation requires further research and development.

6.3.2.3. Stability

Ensuring the stability and longevity of NPs in soil environments is crucial for sustained remediation.

7. POTENTIAL RISKS AND ENVIRONMENTAL IMPACT

While NPs offer significant advantages for soil remediation, their environmental impact and potential risks cannot be overlooked. The unnecessary build-up of NPs in the environment can lead to toxicity in plants and other organisms. Understanding the post-treatment behavior of NPs and their movement in ecosystems is crucial. Strategies for the safe design, application, and disposal of NPs must be developed to mitigate these risks [98,99].

8. CONCLUSION

NPs provide innovative solutions for the remediation of HM-contaminated soils through various physicochemical and biological mechanisms. Their unique properties make them highly effective in reducing the toxicity and mobility of contaminants. However, careful consideration of their environmental impact and potential risks is essential for sustainable application. Further research is needed to optimize NP-based remediation techniques and ensure environmental safety.

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10. DECLARATION OF CONFLICT OF INTEREST

There is no conflict of interest.

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**Bibliographical Sketch*

Rajesh Kumar is a Research Scholar at Ranchi University with a focus on nanotechnology applications in Medical technology and Agricultural technology. His research contributions span several key areas, including the genetic variability of Brassica juncea under acidic soil conditions, and the development of nanomaterials for biomedical applications. Notable works include "Induction of variability for yield components in Indian mustard under acidic soil regime of Jharkhand" (2021), which examines mutation breeding and genetic diversity in crops, and "Genetic Variability for quantitative traits in F3 families of Brassica juncea" (2018). Kumar has also explored the therapeutic potential of nanomaterials, as reflected in "Characterization Techniques for properties of nanomaterial and its significance: A review" (2022) and "Transition Metal Oxide-Based Nanoparticles: Role as Catalyst" (2021). His ongoing research in pharmaceutics includes developing a sustained-release matrix system for Metformin Hydrochloride (2024). Kumar's work contributes to advancing knowledge in both agricultural and biomedical fields..