International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2025; 9(1): 488-504
www.biochemjournal.com
Received: 15-11-2024
Accepted: 19-12-2024

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Emerging techniques of soil remediation: Nanotechnology and bioremediation approaches: A review

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DOI: https://doi.org/10.33545/26174693.2025.v9.i1f.3560

Abstract
Soil pollution is one of the critical issues that affects environmental health, agricultural productivity, and overall balance of an ecosystem. The contamination of soil with heavy metals, organic pollutants, and hazardous substances is a result of industrial discharge, agricultural practices, and urbanization. Traditional remediation techniques, such as excavation and chemical treatments, are effective but expensive and often cause secondary pollution. Emerging technologies include nanotechnology and bioremediation. These are very novel and promising, sustainable remediation alternatives that use adsorption, catalytic reduction, or chemical reduction by nanoparticles, in contrast to traditional techniques. Microbial and plant-based biodegradation or biotransformation can be involved in bioremediation. It describes the present trends, mechanisms, and successful application of both approaches, particularly in terms of individual advantages, but also concerning their potential integrated approach to treating multi-component contaminant soil matrices more effectively.

Keywords: Nanotechnology**,** bioremediation, catalytic, microbes

Introduction
It is through the widespread practice of industrial activities, high intensity of agricultural practice, and increased rate of urbanization that results in the constant pile-up of hazardous heavy metals and organic pollutants (Kumar, D., & Khan, E. A. 2021) [58]. These toxins stand to face high risks to the fertility of soil, food safety, and human health. Traditional remediation techniques, which include excavation, soil washing, and chemical treatments, have been quite effective but labor- and cost-intensive. Most of them result in secondary issues related to environmental impact, such as waste and toxicity to non-target organisms. There is an increasing need for sustainable solutions, which has highlighted new avenues such as nanotechnology and bioremediation. These techniques hold great promise since they can target the pollutants precisely, have minimal environmental impacts, and be cost-effective as well as ecologically friendly alternatives for soil restoration. This paper reviews recent advancements in these emerging techniques, focusing on their mechanisms, applications, and synergistic potential to tackle complex challenges of soil contamination.
industrialization/urbanization is adding solid wastes, chemicals and solvents, and other persistent organic and inorganic materials to different environmental matrices (Midhat *et al.*, 2019) [70]. The advancement in nanotechnology and nanoscience is opening new avenues to research and development in almost every field of science. It is an expanding research field that involves structures, devices, and systems with unique properties owing to the arrangement of their atoms at the nanoscale (1-100 nm) (Bayda *et al.*, 2019; Rajput *et al.*, 2021b) [14, 87, 89]. In recent decades, nanotechnology has been used in a range of contexts, notably medicine, textiles, pharmaceutics, electronics, optics, cosmetics, sports, and many others. The application of NPs in agriculture was accepted at the turn of the twenty-first century (Fraceto *et al.*, 2016) and has already exceeded over 232 products that are offered for different purposes of agricultural utilization (Rajput *et al.*, 2021a) [87, 89]. Furthermore, it also did not become stagnant regarding its application within environmental restoration areas

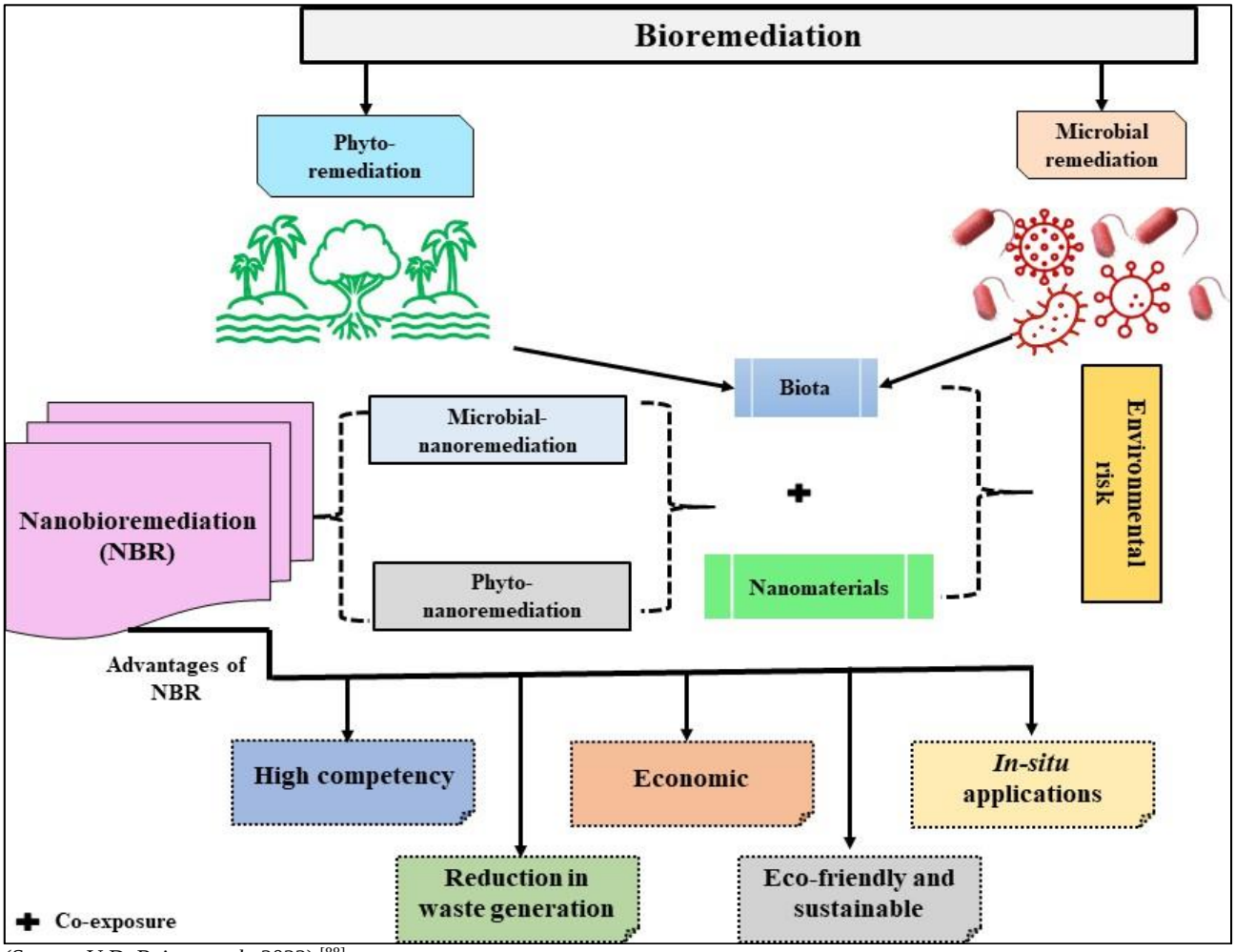
(Guerra *et al*., 2018; Singh *et al*., 2020) [43, 100].

Recently, nanobioremediation (NBR) was declared as a technology for cleaning up environmental contamination by accelerating natural biodegradation processes using NPs. NBR is defined as a process that uses NPs with microorganisms, or plants to eradicate hazardous contaminants from the soils (Cecchin *et al.*, 2017) [21]. Afterwards, specific NBR methods are outlined according to the kind of microorganism involved in the process of remediation of contaminants, namely nanophytoremediation, and microbial nanoremediation (Burachevskaya *et al.*, 2020) [19]. With the intensification in the costs of chemical as well as physical processes, microbes- and plant-mediated NBR technologies are gaining more focus. Coming to the benefits of NBR, there are many reasons why nanotechnology is integrated with bioremediation. For instance, the large surface area per unit mass of NPs means that more particles can contact the environment to enhance the remediation process (Kaur *et al.*, 2018) [52]. Therefore, the NBR aims to reduce pollutant concentrations to a minimum risk-based threshold and lower the secondary environment impacts. Secondly, this form of reclamation integrates both nanotechnology and bioremediation to result in a remediation process that is not only faster, but also more efficient and environmentally benign compared to the standalone method (Patil *et al.*, 2016; Kumar *et al.*, 2021) [81, 58, 59].

However, with each step forward of the process of remediation, there are specific explicit merits as well as demerits that need to be considered at each place. In a nutshell, after such an extensive literature survey, it can be finally concluded that bioremediation with nanotechnology seems to appear as a practical alternative to traditional remediation technologies either in tandem or in tandem with them. However, there is still more study and development measures to be taken for these types of sustainable technology before they can reach the market fully.

NBR has several benefits because of the properties of nanotechnology. For example, the large surface area-to-mass ratio of NPs increases their interaction with the environment, thereby accelerating the remediation process (Kaur *et al.*, 2018) [52]. NBR aims to reduce pollutant concentrations to acceptable levels while minimizing secondary environmental impacts. By combining nanotechnology with bioremediation, this approach creates a more efficient, faster, and environmentally friendly remediation process compared to traditional methods (Patil *et al.*, 2016; Kumar *et al.*, 2021) [81, 58, 59].

Though full of promise, every remediation technology has site-specific advantages and disadvantages that will have to be assessed on-site. Overall, an exhaustive search through the published literature shows promise in nanotechnology with bioremediation providing an alternative mode of remediation for the use in either augmentation or standalone process. Further, further researches and developments should be carried out in order for such sustainable technologies to be thoroughly commercialized.



(Source, V.D. Rajput *et al.*, 2022) [88]

Fig 1: Image of Bioremidation

Sources and Types of Soil Pollution

Soil is an intricate and crucial ecosystem that offers a variety of critical ecosystem services. These services include provisioning, such as food, fiber, freshwater, and timber; regulation services, which cover climate control, erosion prevention, and flood mitigation; cultural services that encompass spiritual and aesthetic value; and supporting services, including provision of physical support for plants, animals, and human infrastructure (Datta *et al.*, 2025) [26]. Soil health is defined as the ability of the soil to function as a dynamic, living system within an ecosystem, supporting plant and animal productivity, enhancing water and air quality, and promoting overall well-being.

Soil is a dynamic, naturally occurring commodity that, comprising gases, minerals, salts, organic and inorganic matter, as well as living organisms, creates both an activity window of essential biological, chemical, and physical properties very sensitive to transformations from both natural processes and human activities (Wise, D. L. 2000) [111]. These include natural processes such as volcanic eruptions, forest fires, and weathering of ores, among others. Anthropogenic activities that contribute to the degradation of soil include industrial waste disposal, agricultural practices, and the use of chemical fertilizers and pesticides (Genske, D. D., & Genske, D. D. 2003) [40].

Table 1: Role of engineered NPs in the phytoremediation of Pb and Cd from the soil

Pollution	Applied NPs	Mode of action of NPs	Plant name	Remarks	Reference
	nZVI	Lower concentration of nZVI promoted plant Growth	*Kochia scoparia*	100-500 mg/kg of nZVI enabled 857.18 µg per pot of Pb accumulation in the plant	Zand and Tabrizi, 2020 [124]
				With nano-hydroxyapatite the	
	Nanohydroxya	Promoted plant growth	*L. perenne*	concentration of Pb in the root	
Pb	patite	through phosphate		was reduced by 2.86- 21.1% and	Ding *et al*., 2015 [30]
		mobilization in the soil		in the shoots 13.19-20.3%	
				reduction of Pb was observed	
		Lower concentration of	*L. perenne*	Accumulated maximum	
	nZVI	nZVI promoted plant		concentrations of Pb in the root	Huang *et al*., 2018 [115]
		Growth		and shoot of the plants	
	Nanohydroxya	Reduced phytotoxicity,	*L. perenne*	The 21.97% remediation	
	patite	and enhance plant		efficiency was observed within 6	Jin *et al*., 2021 [55]
		Growth		weeks	
				Concentration (100 to 300	
		Improved germination	*Glycine max*	mg/kg) dependent increase in	
	TiO2	and photosynthetic		the uptake of Cd was observed	Singh and Lee, 2016 [61]
Cd		capacity of the plant		(128.5 µg -507.6 µg of Cd per	
				plant)	
				Increase in the accumulation of	
	nZVI	Promoted plant growth	*Boehmeria*	Cd in the leaves by 31-73%,	Gong *et al*., 2017 [47]
			Nivea	stems by 29-52%, and roots by	
				16-50% were recorded	
			Sorghum	Enhanced uptake of Pb and Cd of	
Pb, Cd	nZVI	Promoted plant growth	*Bicolor*	the concentration 50 mg/kg to	Cheng *et al*., 2019 [23]
				1000 mg/kg	
		Reduced seed	*Brassica*	Pb was reduced by 1.2-3.8-folds	
Pb, As	CNT with	germination; however,	*Rapa*	and significantly reduced As	Awad *et al*., 2019 [125]
	biochar	toxicity was modulated		accumulation in the soil	
		by biochar			
As, Cd,			*Helianthus*	Reduced up to 60% uptake of As,	
Pb, Zn	nZVI	Stabilized HMs	*annuus*,	Cd, Pb, and Zn in roots and shoots	Vítková *et al*., 2018 [126]
			L. perenne	compared to the control plants	
		Improved the	*Secale*	Accumulation of Pb in	Moameri and Khalaki, 2019 [127]
		availability of Pb and	*Montanum*	the roots was achieved up to	
Cd, Pb	Nano-silica	Cd to the plants, and		533.6 mg/kg DW and Cd up to	
		also promoted the		208.6 mg/ kg DW.	
		growth of the plant			

Source, (Source, V.D. Rajput *et al.*, 2022) [88]

Main causes of soil pollution

The main contributors of soil pollution are human-made chemicals and natural environmental changes (Fayinminnu *et al.*, 2024) [37]. Generally, causes are such as leakage from underground storage systems, veruse of pesticides and fertilizers, seepage of polluted surface water into underground layers and disposal of oil, fuel, and industrial wastes directly into the soil (Emmanuel, O. O. 2022) [33].

Leaching of landfill waste

Both natural and anthropogenic sources constantly expose soil to harmful chemical components, which aggravate environmental contamination (Emmanuel, O. O. 2022) [33]. Industrialization and urbanization further aggravate the problem as they introduce several toxic substances into the environment.

Sources of Soil Pollution

Agricultural Sources: Overuse of fertilizers, pesticides, and irrigation practices that cause salinity and other chemical build-ups (Nelson, M., & Maredia, M. K. 2001) [74]. Non-Agricultural Sources includes industrial waste, mining operations, and smelting activities.

Soil Properties and Pollution Impact

Productivity, filtering, and buffering capabilities of soil ecosystem are dependent upon its structure, depth, humus content, nutrient availability, and the presence of foreign materials (Fageria, N. K. 2012) [34]. Quality of soil cannot be evaluated instantaneously; it is an analysis of the physical, chemical, biological, and biochemical properties altered by changes in the environment and management (Maurya *et al.*, 2020) [67].

Physical properties involve temperature, porosity, bulk density, and water-holding capacity, whereas chemical parameters take into account soil reaction, carbon and nitrogen content, and nutrient composition (Osman, K. T., & Osman, K. T. 2013) [78]. Biological assessments involve microbial activity and include factors such as soil enzymes, respiration, carbon and nitrogen mineralization, and biological nitrogen fixation.

Microbial analysis is particularly useful for monitoring heavy metal contamination because soil microorganisms reflect the health of an ecosystem.

Progressing the Science of Soil Pollution

Modern perspectives recognize the interdependence of soil health with climate change, microbial ecology, and sustainable practices. It is important to integrate advanced technologies and holistic approaches to address the multifaceted challenges posed by soil pollution (Hariram, *et al.*, 2023) [44]. These strategies are necessary for developing a more resilient and sustainable environment, ensuring that soil continues to support life and deliver its ecosystem services.

Nanotechnology in Soil Remediation

Mechanisms of Nanomaterials in Soil Remediation

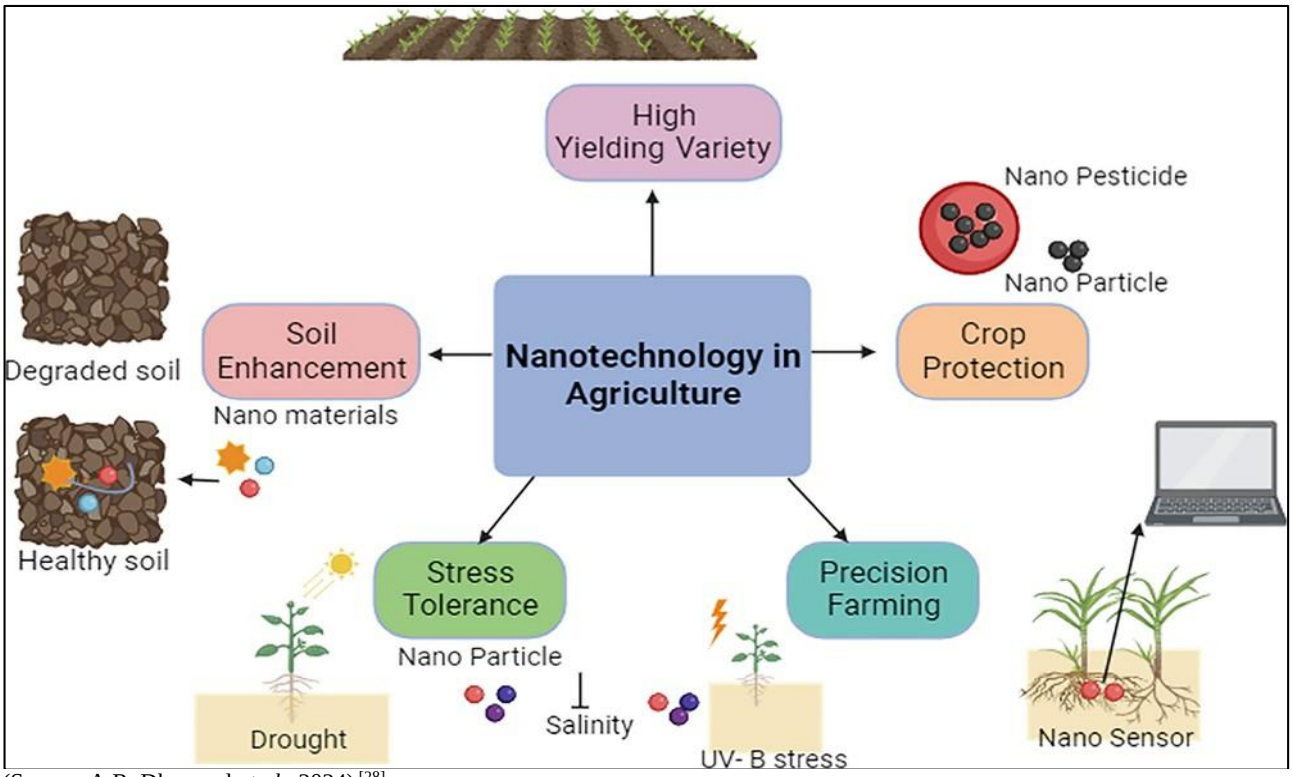
Nanotechnology applications use NPs that have exceptional physical, chemical, and electronic properties to enable application in various modes of soil remediation (Qian *et al.*, 2020) [82, 83]. These mechanisms exploit the high surface area, reactivity, and tunable properties of NPs.

Particles that include iron oxide as well as carbon nanotubes have an exceptional ability to bind with heavy metals, organic pollutants, and other toxic substances as a result of a large surface area as well as surface charge. NPs serve as efficient catalysts for reactions that break down or convert pollutants (Guerra *et al.*, 2018) [43]. For instance, TiO_2 nanoparticles catalyze the photodegradation of organic compounds under UV light. nZVI are very effective at reducing toxic heavy metals such as chromium (Cr6+) into less harmful forms to allow for a safer environment. Nanoparticles can encapsulate the contaminants so that they may be stabilized in that state so that they may not leach out further into the environment (Dhanapal, *et al.*, 2024) [28]. Functionalized nanoparticles can deliver remediation agents to and fro at the contaminated hotspot, enhancing the efficiency of soil restoration. Adsorption: NPs such as iron oxides and carbon nanotubes have a very high adsorption capacity for heavy metals and organic pollutants. Nanoparticles act as catalysts for degradation reactions, for example, the reduction of chlorinated compounds. Zero-valent iron nanoparticles (nZVI) reduce the toxic metals such as chromium (Cr6+) to less toxic forms (Kumari, B., & Singh, D. P. 2016) [61].

Table 2: A Brief Summary of Applications of Nanotechnology in Soil and Water Remediation (Source: Mueller and Nowack, 2010)

S/No	Types of Nanoparticles	Type of Pollutants Remediated	References
1	Carbon-based nanomaterials	Organic and inorganic pollutants	(Jin *et al.*, 2021) [55]
		Fluoride from drinking water	(Mansoori *et al.*, 2009) [128]
	Carbon Nanotubes (CNTs)	Polychlorinated biphenyls, polycyclic aromatic hydrocarbons	(Pan and Xing, 2010) [129]
	MWCNTs	Microorganisms, heavy metals	(Raj Kumar & Gopinath, 2017) [130]
		Heavy metals in soils	(Correia *et al.*, 2019) [131]
	SWCNTs	Microorganisms	(Raj Kumar & Gopinath, 2017) [130]
2	Inorganic-based nanomaterials	Polychlorinated biphenyls (PCBs)	(Hua *et al.*, 2017) [47]
		Chlorinated alkanes, benzenes, dioxins, furans, PCBs, Cr(VI), Ag(I), and Pt(II)	(Hua *et al.*, 2017) [47]
		Microorganisms	(Chatterjee *et al.*, 2009) [101]
	TiO_2 Nanoparticles	Pesticides, dyes, toxic compounds from wastewater	(Meghmala *et al.*, 2019) [69]
3	Organic-based nanomaterials (Dendrimers)	Heavy metals	(Quetel *et al.*, 2010) [86]
		Cu^{2+} from polluted water and soil	(Xu & Zhao, 2005; Guerra *et al.*, 2018) [113, 43]
		Pb(IV) from polluted soil	(Xu & Zhao, 2006) [114]
		Manganese, nitrate, iron, arsenic, CO, SO_2, aliphatic and aromatic hydrocarbons, pharmaceuticals, bacteria, parasites, and viruses	(Guerra *et al.*, 2018) [43]
		Organic compounds	(Diallo *et al.*, 1999) [29]
4	Composite-based nanoparticles	Carbon nanotubes + ZnO nanoparticles: Ions, gaseous molecules, low molecular weight organic compounds	(Zimmerman & Lawless, 2001; Triano *et al.*, 2015) [123, 106]
		Polymeric CNT + Calixarenes and thiacalixarenes: Congo red dye from aqueous environments	(Arabi *et al.*, 2019; Khare *et al.*, 2019) [10, 53]
		Ceramic filters + Poly(amidoamine) and poly(ethyleneimine) dendrimers: Cd^{2+}, Pb^{2+}, and p-nitrophenol from water	(Rizwan *et al.*, 2014) [92]
		nZVI + noble metals: Organic chlorine and hydrogen	(Karn *et al.*, 2009) [51]

(Source, Yarima *et al.*, 2020)



(Source, A.R. Dhanapal *et al.*, 2024) [28]

Fig 2: Nanotechnology approaches in agriculture

Nanotechnology has emerged as a transformative approach to address soil pollution, enhancing phytoremediation and bioremediation processes (Kumari, B., & Singh, D. P. 2016) [61]. Its potential lies in the unique properties of nanoparticles, such as their small size and high surface area, which enable effective remediation of pollutants.

Soil Pollution and Its Challenges

Heavy metals, pesticides, and POPs drive severe risks to agricultural productivity and food security as well as human health through soil pollution (Fang *et al.*, 2025) [36]. Once again, through bioaccumulation, these contaminants become part of the food chain and further the ecological crisis.

The urgent need for effective remediation of soil mainly arises in conjunction with increased demand for food production, which has resulted in exploitation and degradation of the soil. Traditional approaches to remediation cannot cope with such complex challenges.

Nanotechnology-Assisted Soil Remediation

Nanotechnology comes up with innovative and cost-effective strategies that are also sustainable for cleaning soil contamination due to various forms of contaminants.

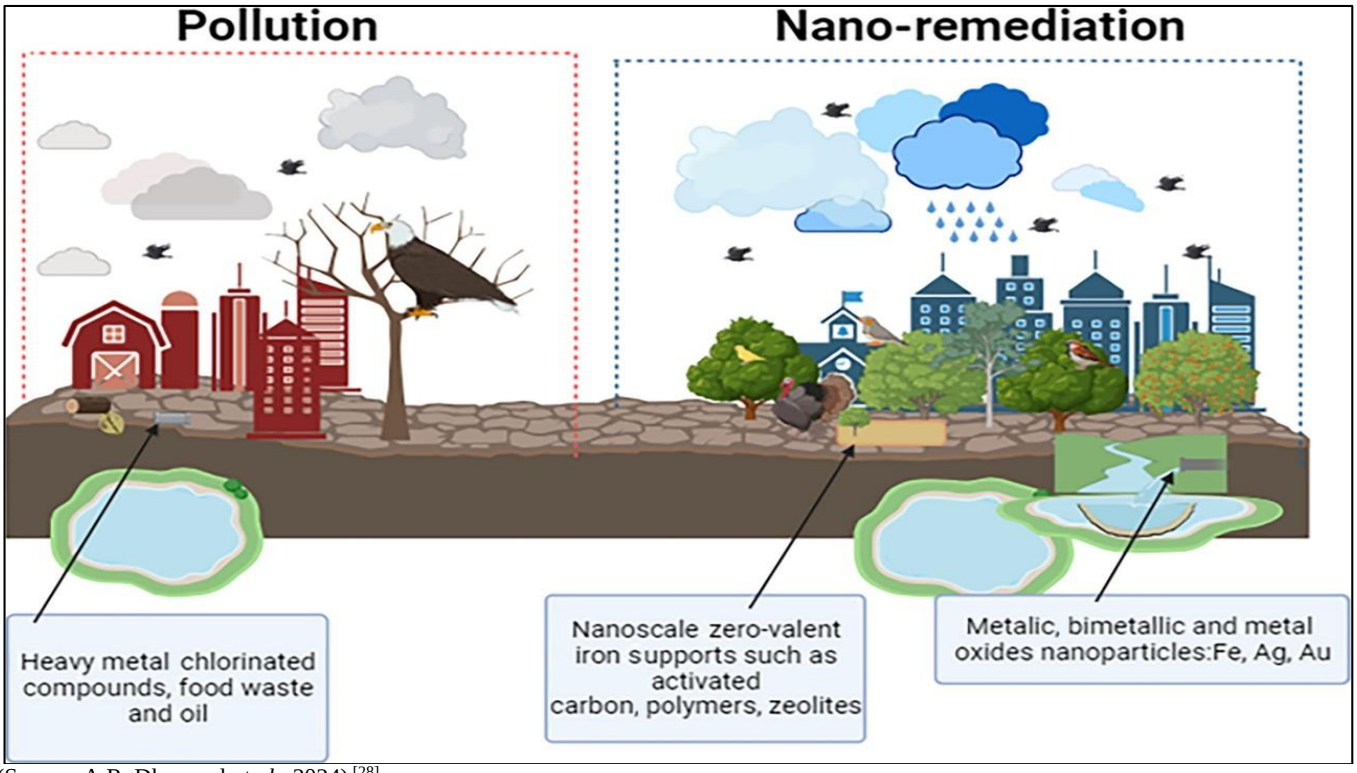
Zero-valent iron (ZVI), magnetic nanoparticles, and nanoclays can immobilize or remove the heavy metals present in the soils contaminated with lead, arsenic, and cadmium (Amarasiri *et al.*, 2021) [8]. Other nanomaterials like TiO_2, carbon-based nanomaterials have also been applied for degrading pesticides and persistent organic pollutants by photodegrading and adsorbing these hazardous chemicals, therefore allowing the removal of harmful chemical contaminants from soils (Gevao, B., & Jones, K. C. 2002) [41].

In addition, nanoenabled phytoremediation enhances plant-based remediation processes by promoting plant growth, increasing pollutant uptake, and detoxifying harmful substances within plants. Nanotechnology also supports microbial bioremediation by supplying essential nutrients or serving as catalysts to accelerate pollutant degradation (Bhatt *et al.*, 2022) [16]. For instance, silver nanoparticles inhibit harmful microbial growth while encouraging beneficial microbial activity in the soil. These applications show the possibility of nanotechnology in reviving polluted soils and its contribution to sustainable agriculture.

Mechanisms of Action

The mechanisms of action for nanotechnology in soil remediation include:

Nanoparticles capture contaminants on their surface, thus removing them from the soil. Reactive nanoparticles transform pollutants into less toxic forms, thus reducing their harmful impact (Patil *et al.*, 2016) [81]. Nanomaterials accelerate the degradation reactions of complex organic pollutants, thus making the remediation process more efficient (Roy *et al.*, 2021) [93]. Nanoparticles immobilize pollutants, thereby arresting their



(Source, A.R. Dhanapal *et al.*, 2024) [28]

Fig 3: Environmental pollution remediation using nano-technological approaches.

Advantages and Disadvantages of Nanotechnology in Soil Remediation

Nanomaterials have enhanced pollutant-bonding and degradation properties; thus, nanotechnology-based soil remediation can be more efficient. Nanoparticles require less amount to ensure considerable remediation. Nanotechnology-based remediation processes are environmental friendly as secondary pollution during remediation is very negligible.

Drawbacks of nanotechnology

Some nanoparticles can pose a potential risk of toxicity to soil organisms and humans, and hence safety issues arise. Large-scale production and deployment of nanomaterials for widespread remediation pose significant challenges. Long-term environmental effects of nanomaterials need comprehensive studies, which might raise regulatory issues in their use.

Nanomaterials Types

Nanomaterials used in soil remediation have presented varied structural, chemical, and functional properties, developed based on the type of contamination. Among them, metal and metal oxide nanoparticles are extensively studied due to their high reactivity and efficiency in targeting a wide variety of pollutants (Yang *et al.*, 2019) [116]. Highly effective in the adsorption of heavy metals and catalytic degradation of organic pollutants. The most outstanding feature of the compound is that it is extremely known for photocatalytic properties, especially when it breaks organic compounds under UV light. ZnO is an excellent antibacterial and pollutant degradation capability (Reginatto *et al.*, 2020) [90, 91]. Carbon-based nanomaterials have versatility and have a high surface area, hence effective in the trapping and degradation of pollutants. Examples include GO - As an adsorbent, a very effective tool for organic contaminants as well as metal ions due to its 2D structure CNTs are excellent for adsorbing hydrocarbons, other organic and inorganic chemicals, and, in general, removing pollutants in trace concentrations (Shubair *et al.*, 2018) [99]. Chemical surface modification enhances binding and degradation. Hydrophilic polymers are designed to target and sequester phase aqueous water solutes. Nanocomposite polymer is a composition of polymer blended with other nanomaterials targeting complex contamination patterns. Bimetallic nanoparticles are two metals, like iron and palladium, that improve reactivity and increase the scope of pollutants to be treated. These particles are very effective in the simultaneous reduction and degradation of organic and inorganic contaminants (Mohanraj *et al.*, 2022) [71]. Magnetic nanoparticle materials allow for easy recovery post-remediation, reducing secondary pollution. Examples include magnetite (Fe_3O_4) for heavy metal adsorption and removal of organic pollutants. Bio-nanomaterials have an origin from biological processes or biologically altered material that exhibits environmental friendliness for degrading pesticides and nutrient recaptures in soils. Modern nanomaterials development seeks to render these more specific, scalable, and eco-friendly, thus enlarging their applications in sustainable remediation of contaminated soils (Debnath *et al.*, 2020) [27].

Metal and metal oxide nanoparticles include iron oxide, titanium dioxide, and zinc oxide NPs, widely used because of their high reactivity (Blundell *et al.*, 2021) [17]. Carbon-based Nanomaterials Graphene oxide and carbon nanotubes efficiently adsorb organic pollutants. Functionalized polymers improve pollutant binding and degradation.

Table 3: Different Nanoparticles Were Used for Bioremediation

S. No.	Nanoparticles	Application/Advantage	Ref
1	Silica nanoparticles	Photocatalytic degradation	(Mohanraj *et al.*, 2022) [71]
2	Graphene oxide and carbon nanotubes	High surface area, presence of pores between MOFs and platforms, hydrophobic and/or π−π interactions, and diverse morphological characteristics of mixed nanocomposites	(Ahsan *et al.*, 2020) [6]
3	Enzyme immobilized nanoparticles	Immobilized laccase oxidation	(Ji *et al.*, 2017) [49]
4	Zirconia nanoparticles	Strong electrostatic interactions and chemisorption between zwitter ions	(Debnath *et al.*, 2020) [27]
5	Electrospun cyclodextrin fibers	Bacterial bioremediation	(San Keskin, *et al.*, 2018) [94]
6	Mesoporous organosilica nanoparticles (MONs)	Increased surface area and conjugation due to ferrocene-mediated noncovalent interactions	(Yang *et al.*, 2019) [116]
7	Cobalt and cobalt oxide nanoparticles	Utilization of sunlight and high surface area	(Adekunle *et al.*, 2020) [3]
8	NiO and MgO nanoparticles	Zn^{2+} adsorption is exothermic and chemical, while Cu^{2+} and Cr^{3+} adsorption is spontaneous, endothermic, and physical	(Abuhatab, *et al.*, 2020) [2]
9	Electrospun nanofibrous webs	Biological elimination of color	(Sarioglu *et al.*, 2017) [96]

(Source, A.R. Dhanapal *et al.*, 2024) [28]

Nanotechnology in Agricultural Soil Remediation: Innovations and Sustainable Practices

Remediation of contaminated agricultural soils is considered an essential area of research. This problem can now be approached using innovative nanotechnology (Tian *et al.*, 2020) [104]. Recent investigations include a large family of nanomaterials in terms of potential soil remediation. In such ways, this article portrays an interdisciplinary relationship between nanotechnology and environmental science.

A primary area of research is the application of nZVI particles, which have been shown to be highly reactive in breaking down various pollutants ((Zhang *et al.*, 2018) [31]. The particles can be engineered to target specific contaminants, and this may provide a promising avenue for improving soil quality. Another area of nanomaterials, such as titanium dioxide (TiO2) and carbon-based nanoparticles, has been proven to be very effective in adsorbing and transforming pollutants, thus reducing the negative impacts of agricultural practices on soil health (Xue,W *et al.*, 2018) [115].

Furthermore, the advent of nanoscale delivery systems, such as nanocarriers and nanosensors, has allowed precision agriculture to better manage pollutant issues (Chang *et al.*, 2019) [48, 116]. These nanodevices make it possible for remediation agents to be delivered in a more targeted manner, while real-time monitoring of the soil conditions becomes possible, enabling a more proactive and sustainable method of soil cleaning (Qiao *et al.*, 2017) [84].

Thereby, the assessment of risks involving the use of nanomaterials in agriculture is essential. Understanding the behavior, transport, and toxicity of nanoparticles provides a means for ensuring the long-term safety and sustainability of soil remediation techniques based on nanotechnology (Fan *et al.*, 2016) [35].

The integration of nanotechnology into agricultural soil remediation has great potential, providing innovative and efficient solutions to the challenges of soil pollution (Apul *et al.*, 2016) [9]. This review aims to summarize recent developments in this field, focusing on both the opportunities and challenges of applying sustainable, environmentally friendly practices in modern agriculture **(**Vilardi *et al.*, 2018) [109].

Applications

Nanotechnology has successfully been applied in different areas of soil remediation, which signifies its applicability and effectiveness for solving the challenge of various forms of contamination.

Iron oxides, titanium dioxide, and nZVI have been used to successfully remove toxic heavy metals, including lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), from contaminated soils. These materials adsorb or reduce metal ions into less bioavailable or less toxic forms, thereby reducing their impact on the environment **(**Huang *et al.*, 2019) [48, 116].

Organic pollutants such as hydrocarbons, pesticides, dyes, and polychlorinated biphenyls can be photo-degraded with the help of photocatalytic nanoparticles like TiO_2 with UV light exposure. Carbon nanomaterial-based adsorbents in the form of graphene oxide or carbon nanotubes can well adsorb organic contaminants and eventually decompose the same **(**Boente *et al.*, 2018) [24].

Nanotechnology has been merged with other remediation techniques to provide better efficiency. For instance, nanomaterials have been incorporated with phytoremediation to provide better uptake by the plants of pollutants, while the coupling of nanoparticles with bioremediation accelerates the microbial degradation process **(**Czinnerová *et al.*, 2020) [24].

Studies on nanoparticles have been performed to recover nutrients from contaminated sites that are used for amendment purposes, thereby improving soil health and fertility after remediation. Due to their ease of recovery, magnetic nanoparticles have been considered for the cleaning and removal of hydrocarbons from soil from oil spills and provide a reusable solution **(**Qu *et al.*, 2017) [24].

These applications show that nanotechnology can treat a broad variety of contaminants with flexibility and are opening pathways to its larger scale application in soil remediation Chen *at al.*, 2020). Heavy metal removal, like the removal of lead, cadmium, and arsenic, from contaminated soils. Organic pollutant degradation: like NPs degrades hydrocarbons, pesticides, and dyes. Inclusion of NPs in conjunction with other technologies, for instance, phytoremediation (Wang *et al.*, 2015) [110].

Table 4: Recent Studies Employing Nanoremediation Methods for Soil Remediation

Nanomaterial	Contaminant	Experimental Condition	Important Results	Ref.
PVP-nZVI	Trichloroethylene (TCE)	TCE initial concentration 1 mg/kg; PVP-nZVI dosage 0.01 g/g; size of prepared PVP-nZVI ~70 nm; isoelectric point ~8.5	TCE removal efficiency was ~84.73%.	(Tian *et al.*, 2020) [104]
nZVI	Cr(VI)	Five ratios tested (1000/140 to 1000/11 mg/mg); nZVI injection pressure (10, 30, 100 kPa); Cr(VI) initial concentration 800 mg/kg	Removal efficiency reached 98% at 1000/11 mg/mg ratio; pressure of 30 kPa was most efficient.	(Reginatto *et al.*, 2020) [90, 91]
nZVI and Cu-modified nZVI	Nitrate	Initial nitrate concentration 45 mg/L; flow rate 5 mL/min; residence time 99 min; single-layer nZVI or two-layer Cu-modified nZVI	Single-layer nZVI removed >97%; two-layer Cu-modified nZVI achieved complete nitrate removal.	(Shubair *et al.*, 2018) [99]
Rhamnolipid-modified nZVI	Cd(II), Pb(II)	Sediment weight 0.5-2 g; R-nZVI concentration 2.5-10 mL; reaction time 0-42 days	Effective for heavy metal immobilization on river sediment.	(Xue,W *et al.*, 2018) [115]
nZVI	DDT	nZVI dosage 5% (w/w); reaction time 60 min	DDT removal: 85% by nZVI, 11% by ZVI, showing nZVI's superiority for DDT remediation.	(Blundell *et al.*, 2021) [17]
MWCNTs	Total petroleum hydrocarbons (TPH)	TPH initial concentration 11,000 mg/kg; microwave treatment 15-60 s; CNT concentration 1-5 wt%	Microwave time and CNT concentration significantly enhanced TPH removal from soil.	(Apul *et al.*, 2016) [9]
MWCNTs	Cr(VI)	Cr(VI) initial concentration 5-60 mg/L; citric acid concentration 25-250 mg/L; MWCNT concentration 1.25 mg/L	At pH 5.0, Cr(VI) adsorption capacity was 8.09 mg/g for MWCNT-COOH and 7.85 mg/g for MWCNT-OH.	(Zhang *et al.*, 2018) [31]
Modified Carbon Black Nanoparticle (MCBN)	Heavy metals, petroleum	Cd initial concentration 10 mg/kg; Ni 100 mg/kg; petroleum 2000 mg/kg; remediation time 60 days; MCBN dosage 1% (w/w)	Decreased heavy metal availability and enhanced plant growth in contaminated soil.	(Chang *et al.*, 2019) [48, 116]
SWCNTs and MWCNTs	DDT, HCH	CNT dosage 0.058-0.29 wt%; DDT initial concentration 3 mg/kg; HCH initial concentration 1 mg/kg; remediation time 4 months	Effective for DDT and HCH remediation; results dependent on dose, type, and sediment-sorbent contact time.	(Zhang *et al.*, 2017) [118]
MWCNTs	Crude oil	MWCNT concentration 0.1-1 wt%; crude oil concentration 0.5-5 wt%; remediation time 30 days	Enhanced hydrocarbon degradation by increasing microbial population.	(Abbasian *et al.*, 2016) [1]
MWCNTs and Activated Carbon (AC)	DDT, HCH	DDT initial concentration 14 ng/g; HCH 5.5 ng/g; AC and MWCNT dosage 1-2 wt%; reaction time 30-150 days	AC was more effective due to its high specific surface area; promising for in situ soil remediation.	(Hua *et al.*, 2017) [47]
Al_2O_3, SiO_2, TiO_2	Zn, Ni, Cd	Nanoparticle dosage 1-3 wt%; remediation time 30 days	SiO_2 effective for Zn, Cd, and Ni in calcareous soils; Al_2O_3 better for Cd and Zn in non-calcareous soil.	(Naderi Peikam, E.; Jalali, M, 2018) [73]
Biochar-supported Iron Phosphate	Cd	Cd initial concentration 4.25-132.23 mg/kg; remediation time 28 days	Reduced Cd by 81.3% within 25 days.	(Qiao *et al.*, 2017) [84]
Goethite Nanospheres (nGoethite) and nZVI	As	nZVI dosage 0.5-10 wt%; nGoethite dosage 0.2-2.5 wt%; As initial concentration 85 mg/kg	Promising for As immobilization; nGoethite effective at lower dosages.	(Baragañ *et al.*, 2020)
MNPs	Cd, Pb	Cd concentration 10.91 mg/kg; Pb 190 mg/kg	Organic content reduced metal removal efficiency; MNPs maintained soil composition.	(Fan *et al.*, 2016) [35]
Fe_3O_4@C-COOH MNPs	Pb	Pb initial concentration 737.34 mg/kg; Fe_3O_4@C-COOH MNPs dosage 0.6-4.0 wt%; remediation time 10 days	Significantly reduced Pb migration; highly effective remediation technology.	(Ma *et al.*, 2020) [66]
MNPs	As, PAH, TPH	MNP dosage 0.2-5 wt%; As initial concentration 1305 mg/kg; PAH 6777 µg/kg; TPH 384 mg/kg	1% MNP dosage immobilized 42% As; 5% dosage immobilized 92.3%. PAHs and TPH reduction at 89% and 49%, respectively.	(Baragaño *et al.*, 2020)

Table 5: Recent Studies Employing Combined Nanoremediation Technologies

Nanomaterial	Contaminant	Experimental Conditions	Important Results	Reference
CNTs-nZVI	Cr(VI), Se, Co	Dosage: 3 g/L, Initial concentration: 1-10 mg/L, pH: 6-8	100% Cr(VI) removal using nZVI; CNTs-nZVI showed high removal efficiencies for Se (90%) and Co (80%).	(Vilardi *et al.*, 2018) [109]
CMC-nZVI/BC	Cr(VI)	Dosages: 11, 27.5, 55 kg/g; Initial concentration: 800 mg/kg	Immobilization efficiency increased from 19.7% to 100% as dosage increased from 11 to 55 kg/g after 21 days.	(Zhang *et al.*, 2018) [31]
Biochar-nZVI	Chlorinated solvents	Dosage: 30 g/L, Injection depths: 3.5, 4.5, 5.5 m	Biochar improved solvent removal, sustaining efficiency over 42 days, compared to re-bonding after nZVI alone.	(Qian *et al.*, 2020) [82, 83]
nZVI with compost	Hydrocarbons (TPH, PAHs), heavy metals	TPH: 104.3 mg/kg, PAHs: 2.25 mg/kg	Combination reduced aliphatic hydrocarbons by 60% and decreased ecotoxicity in soil biopiles.	(Blundel *et al.*, 2021) [17]
PVP-coated magnetite NPs with oil-degrading bacteria	Crude oil	Oil concentration: 375 mg/L, NPs dosage: 18 mg/L	NPs removed 70% of oil within 1 h; combined with bacteria, complete removal achieved within 48 h.	(Alabresm *et al.*, 2018) [7]
nZVI-EK	Chlorinated ethenes (CEs)	nZVI dosage: 3 g/L, DC voltage: 24 V	Achieved 70% reduction in cis-1,2-DCE; enhanced soil microbial activity and organohalide-respiring bacteria growth.	(Czinnerová *et al.*, 2020) [24]
Soil washing with nZVI	As, Cu, Hg, Pb, Sb	nZVI dosage: 16 wt%	High recovery yield for Pb, Cu, and Sb in magnetic fractions; enhanced soil washing efficiency.	(Boente *et al.*, 2018) [18]
ACF-nZVI	Cr(VI)	Initial concentrations: 5, 10 mg/L	Full removal in acidic conditions within 1 h; removal involves adsorption and reduction to Cr(III).	(Qu *et al.*, 2017) [85]
PS-Z/nZVI	TCE	TCE: 0.15 mM, Z/nZVI dosage: 84 mg/L, PS: 1.5 mM	98.8% TCE removal at pH 7 within 2 h; effective across pH range 4-7.	(Huang *et al.*, 2019) [48, 116]

Table 6: Nanomaterials and Their Efficacy in Water Remediation

Nanomaterial	Contaminant	Experimental Conditions	Key Results	Reference
PEI-nZVI	PCE, TCE, 1,2-DCE	TCE: 94,000 µg/L; 1,2-DCE: 2800 µg/L	Full removal of DNAPLs within one day post PEI-nZVI injection.	(Lin *et al.*, 2018, Mdlovu *et al.*, 2019) [64, 68]
S-nZVI	TCE	TCE: 20 mg/L; S-nZVI to BC ratio: 1:1-3:3; pH: 3-9; pyrolysis: 300-700°C	Effective degradation and adsorption with BC mass ratio and pH influencing results; minimal pH effects.	(Chen *at al.*, 2020) [82, 83]
S-nZVI	TCE	pH: 5.57-8.02; TCE: 30 mg/L; Aging: 10-30 days	Best results at Fe/S molar ratio of 60 and pH > 7.	(Dong *et al.*, 2018) [31]
nZVI/Cu	Cr(VI)	Cr(VI): 10-15 mg/L; nZVI/Cu: 0.4 g/L; pH: 5-9; Temperature: 293-313 K	Achieved 94.7% removal at pH 5 and 303 K.	(Zhu *et al.*, 2018) [122]
nZVI	Cu(II), Ni(II)	Cu: 1000 mg/L; Ni: 2000 mg/L; Dosage: 0-5%	Complete water remediation; partial immobilization in soil.	(Gil-Díaz *et al.*, 2020) [12, 13]
MWCNTs	Cr(VI)	Cr(VI): 11 mg/L; MWCNTs: 10-50 g/L; pH: 3-9	100% removal at pH 8 with 50 g/L MWCNTs.	(Mpouras *et al.*, 2021) [72]
MWCNTs	Unleaded gasoline	MWCNTs: 0.2-0.8 g; Reaction: 5-120 min	0.7 g of MWCNTs removed gasoline within 5 min.	(Lico *et al.*, 2019) [63]
Al_2O_3/MWCNTs	Cd(II), TCE	Al_2O_3/MWCNTs: 1 g/L; Cd/TCE: 1 mg/L; pH: 4-10	Maximum adsorption for Cd: 19.84 mg/g and TCE: 27.21 mg/g.	(Liang *et al.*, 2015) [62]
Fe/Al BNPs	Cr(VI)	Cr(VI): 4-200 mg/L; Fe/Al BNPs: 2.5 g/L	Superior removal with Fe/Al BNPs at 1.47 g/g efficiency.	(Ou *et al.*, 2020) [79]
FeS NPs	Cr(VI)	Cr(VI): 204.84-3464 mg/kg; FeS NPs: 28.2-117 mg/L	Achieved 1046.1 mg Cr(VI) removal per gram FeS NPs; pH significantly affects efficiency.	(Wang *et al.*, 2015) [110]
Fe-Me binary oxide NPs	Selenite (Se(IV))	Se(IV): 0-10 mg/L; Fe-Mn NPs: 0.05 g/L; pH: 7	Langmuir adsorption: 109 mg Se(IV) per g Fe-Me NPs.	(Xie,W *et al.*, 2020) [22]
Fe/Ni BNPs	Tetracycline	Tetracycline: 100 mg/L; Fe/Ni BNPs: 1 g/L; Ni: 1-5 wt%; Aging: 5-90 days	82.3-92.5% removal efficiency initially; declines over time due to oxidation.	(Dong *et al.*, 2018) [31]
Fe/FeS MNPs	Cr(VI)	Cr(VI): 10-80 mg/L; S/Fe ratio: 0.07-0.207; pH: 3.5-9	Optimal removal at S/Fe molar ratio of 0.207, fitting Langmuir isotherm model with sorption of 69.7 mg/g.	(Gong *et al.*, 2017) [47]
Magnetic ligand NPs	Cd(II), Pb(II)	Cd/Pb: 1-100 mg/L; Mag-Ligand: 0.2 g/L; pH: 4-10	Quick removal (Cd: <2 h, Pb: <15 min); reusable via simple acid wash.	(Huang *et al.*, 2018) [115]
MMSNPs	U(VI)	U(VI): 2.5×10^{-5} M; MMSNPs: 0.075 g in 7.5 mL artificial groundwater	Efficient U(VI) removal; capacity reaches 133 g U(VI) per g MMSNPs.	(Li, *et al.*, 2016) [35]

Challenges and Limitations

Nanomaterials have high potential, but several major drawbacks prevent their general use in soil remediation. First, some of these materials are potentially toxic to beneficial soil organisms, such as bacteria, fungi, and earthworms (Huang *et al.,* 2015) [115]. The deposition of nanoparticles in soil ecosystems could interfere with crucial biological processes necessary for maintaining healthy soils. Furthermore, some nanomaterials do not degrade readily in natural environments, which can cause them to persist over time and potentially bioaccumulate in the food chain (Li, *et al.*, 2016) [35].

Scalability is another critical issue, as scaling up from laboratory-scale research to field applications poses technical and economic challenges. Synthesizing, deploying, and recovering nanoparticles in large quantities is resource-intensive and difficult to achieve (Xie,W *et al.,* 2020) [22]. Economic feasibility also presents a barrier, with high production and application costs making nanotechnology inaccessible for poor regions or large-scale operations. Developing inexpensive production methods is crucial for practical applications.

Lack of clear regulations also exists in regards to the handling and disposal of nanomaterials, with this creating concerns about risks from human health exposure and environmental damages Gong *et al.,* 2017) [47]. Strictly assessed safety levels and monitoring protocol are required as a solution. Recovery of recovered nanoparticles after their remediation becomes equally important by which secondary pollution from them can be avoided, yet techniques for its recycling or environmentally safe disposal is still under way (Liang *et al.,* 2015) [62].

Lastly, there are few knowledge items on the long-term environmental implications of nanotechnology and public anxiety over its safety, which could be considered an obstacle to acceptance and implementation. Interdisciplinary research, technological innovation, and appropriate regulatory frameworks would form the core that could unlock all the potential uses of nanotechnology in sustainable remediation of contaminated soils.

Bioremediation Approaches

Principles of Bioremediation

Bioremediation is a natural and environmentally friendly method of soil remediation, utilizing the capabilities of living organisms to degrade, transform or stabilize contaminants (Kumar *et al.,* 2018) [60]. It is particularly effective for organic pollutants and, to some extent, inorganic contaminants like heavy metals when integrated with other strategies.

This method employs several biological processes and agents in combating soil contamination. Microbial remediation employs bacteria, fungi, and archaea that use pollutants, such as hydrocarbons, pesticides, and polyaromatic hydrocarbons (PAHs), as sources of energy or nutrients (Kumar *et al.,* 2011) [57]. Advanced genetic engineering has additionally improved microbial strains with enhanced degradative capabilities.

The method uses plants to stabilize, extract, or degrade contaminants through mechanisms like phytoextraction, rhizofiltration, and phytovolatilization (Awa, S. H., & Hadibarata, T. 2020) [11]. Sunflowers are used for heavy metal uptake, and willows help degrade hydrocarbons.

Enzymatic bioremediation refers to the application of free enzymes or enzyme-producing microbes that degrade pollutants into less harmful products (Bhandari *et al.,* 2021) [15]. Among such enzymes, laccases and peroxidases are effective in the degradation of POPs. Similarly, mycoremediation uses fungi, particularly white-rot fungi, which can degrade lignin and complex organic pollutants through an enzymatic pathway, thus it is applicable in the treatment of industrial wastes and contaminated soils (Okino *et al.,* 2019 [77].

Advances in bioremediation involve optimizing the environment, particularly the pH, temperature, and oxygen levels; understanding microbial ecology; and designing more efficient organisms (Dvořák *et al.,* 2017) [32]. It is also found that combining bioremediation with nanotechnology or chemical treatments may be used to deal with highly complex contamination scenarios.

Microbial Agents in Bioremediation

The microbial agents form the basis of bioremediation, where microorganisms perform the degradation, transformation, or sequestration of environmental contaminants through various metabolic pathways (Das, S., & Dash, H. R. 2014) [25]. The versatility in the degradation of organic pollutants and inorganic contaminants has classified bacteria as key groups. Species such as Pseudomonas, Bacillus, and Mycobacterium can be mentioned (Fouad *et al.,* 2022) [38]. For instance, Pseudomonas putida is widely recognized for its ability to degrade hydrocarbons, while Bacillus subtilis participates in the detoxification of heavy metals through biosorption and precipitation.

Major agents degrading complex organic pollutants are white-rot fungi, such as Phanerochaete chrysosporium and Trametes versicolor. Their enzymatic activities with laccases, manganese peroxidases, and lignin peroxidases facilitate degradation of persistent compounds like polyaromatic hydrocarbons (PAHs), dyes, and phenols (Nunes, C. S., & Malmlöf, K. 2018) [76].

Extremophilic species of archaea, in particular, have been proved to be good candidates for bioremediation under extreme conditions, such as high salinity or temperature. They are quite efficient in methane oxidation and hydrocarbon degradation within extreme environments such as oil reservoirs.

Mixed microbial consortia, including bacteria, fungi, and other microorganisms, improve the efficiency of degradation through synergistic interactions. Such consortia can address complex contamination scenarios by degrading multiple pollutants simultaneously. For example, a combination of hydrocarbon-degrading bacteria and fungi has been effective in remediating oil-contaminated soils (Wu *et al.,* 2023) [112].

Genetically engineered microorganisms (GEMs) extend the range of bioremediation even further. Recombinant strains of *Escherichia coli* and *Pseudomonas* have been constructed to more effectively degrade pollutants like polychlorinated biphenyls (PCBs) and dioxins than their natural counterparts (Adetunji, *et al.*, 2024) [4].

These various microbial agents demonstrate the heterogeneity and versatility of bioremediation, creating a sustainable means of cleaning polluted soils under different contamination conditions.

Microbes-mediated nanoremediation is an innovative and effective approach in which the degradation and elimination of a wide range of organic pollutants in contaminated ecosystems is mediated through microbial enzymes (Sangwan and Dukare, 2018; Torimiro *et al.,* 2021) [95, 105]. However, environmental factors do have an impact on the effectiveness of pollutant degradation by microbes in polluted soils. The responses of the co-occurrence of microbial communities towards environmental pollutants are variable, and the co-occurrence of co-contaminants can produce unpredictable effects in the bioremediation process (Sangwan and Dukare, 2018; Rajput *et al.,* 2021c; Shende *et al.,* 2021) [95, 98, 98]. However, NBR provides a low-cost and effective remediation of contaminated soil, waste, and groundwater.

Microbe-mediated nanoremediation of xenobiotics is an eco-friendly method through which the persistent toxic chemicals that get accumulated in the environment can be depleted. Microorganisms have the capability to metabolize, transform, and degrade xenobiotic compounds, hence becoming a viable choice for hazardous and toxic waste removal (Agarry and Solomon, 2008) [5]. Their enzymatic systems allow them to use ecologically harmful pollutants as energy and nutrient sources. Advances in the science of bioremediation have been considerably enhanced through interdisciplinary research in analytical chemistry, microbiology, biochemistry, molecular biology, environmental engineering, and nanobiotechnology (Hu *et al.*, 2014; Sangwan and Dukare, 2018; Singh *et al.,* 2020) [46, 95, 100].

The bioremediation process involves the mineralization and detoxification of pollutants, transforming them into simpler inorganic compounds such as water, methane, and carbon dioxide (Liu *et al.*, 2018a; Vázquez-Núñez *et al.,* 2020; Paterlini *et al.,* 2021) [65, 108, 80]. Microorganisms show remarkable versatility in degrading a wide range of organic compounds under both aerobic and anaerobic conditions, making them ideal candidates for bioremediation. These microbes can function in extreme environmental conditions, adding to their suitability for remediation tasks.

Microorganisms also participate in biogeochemical cycles and ecosystem sustainability. Xenobiotic pollutants are converted in aerobic and anoxic conditions where molecular oxygen helps in the degradation of aliphatic and aromatic compounds (Cao *et al.,* 2009; Sinha *et al.,* 2009) [20, 101]. However, among all the microorganisms, bacteria are most efficient and abundant in natural bioremediation processes. They have managed to adapt themselves to utilize the energy from an extensive range of compounds both aerobically and anaerobically using various electron acceptors, such as ferric ions, sulfate, and nitrate. Bacterial genera like *Alcaligenes*, *Acinetobacter*, *Bacillus*, *Escherichia*, *Pseudomonas*, and *Rhodococcus* play important roles in oxygenic breakdown, while *Clostridium*, *Geobacter*, and *Methanococcus* are engaged in anaerobic degradation (Jindrova *et al.,* 2002; Van Hamme Jonathan *et al.*, 2003; Kulkarni and Chaudhari, 2007) [50, 107, 56].

Remediation of persistent soil and water contaminants, such as hydrocarbons, heavy metals, dyes, pharmaceuticals, and other pollutants, is crucial for wastewater and soil treatment. These contaminants cause environmental pollution and are significant risks to ecosystems (Koul *et al*., 2021; Sushkova *et al.,* 2016) [55, 103]. Nanoparticles (NPs), with their high surface area and small size, act as catalysts or adsorbents for contaminants, facilitating effective remediation. There have been reports that NPs catalyze properties in conjunction with biological components to counteract harmful pollutants (Kharissova *et al.,* 2013) [54].

Microorganisms have been highly used to enhance the utilization of NPs in nanobioremediation, and several researchers have shown positive results. The exceptional features of microbes such as their super-hydrophobicity, filtration characteristic, sensitivity to the affinity of the membranes, their programmable functionalities, and their relatively higher surface to volume ratio makes it appropriate for the present technique (Sarwar *et al.,* 2017; Wang *et al.,* 2015; Sangwan and Dukare, 2018) [97, 110, 95]. The approach of microbe-mediated nanoremediation has brought into consideration both the excellence of nanotechnology and that of microbiology.

Applications

Bioremediation techniques have diverse applications across environmental and industrial contexts, effectively addressing soil contamination issues.

One of the key applications is petroleum hydrocarbon degradation, where microorganisms such as Pseudomonas putida and Alcanivorax borkumensis are used to clean up oil spills by digesting hydrocarbons into less hazardous compounds. This process mitigates environmental damage in both terrestrial and marine ecosystems.

Heavy metals detoxification In heavy metal detoxification, the microbial agents significantly play a role in converting the toxic heavy metals, such as mercury (Hg), cadmium (Cd), and arsenic (As), to less toxic or immobilized forms. For example, Bacillus subtilis utilizes biosorption and bioprecipitation mechanisms to sequester the heavy metals to reduce their bioavailability.

It is also highly effective in pesticide remediation, particularly in the degradation of persistent organic pollutants such as DDT, lindane, and atrazine. Fungal species, for example, white-rot fungi, metabolize these compounds using enzymatic pathways, thereby lowering their persistence and toxicity in the environment.

Bioremediation techniques are applied in industrial waste treatment to tackle effluents containing complex organic pollutants. The microbial consortia are used for the degradation of polycyclic aromatic hydrocarbons, dyes, and solvents in contaminated soils and wastewater streams.

For agricultural soil recovery, bioremediation restores soils contaminated with excess fertilizers, pesticides, and heavy metals through phytoremediation and microbial processes. This improves soil fertility while promoting sustainable farming practices. In radioactive waste management, extremophilic microorganisms such as Deinococcus radiodurans have shown promise in stabilizing radioactive elements in contaminated environments, thus providing a biotechnological solution to nuclear waste problems. Finally, bioremediation is used in the treatment of landfill leachate, where microorganisms degrade organic pollutants, thereby reducing the environmental hazards associated with landfills. These applications show the adaptability and efficiency of bioremediation as a sustainable solution for managing soil contamination across diverse scenarios.

Advantages and Challenges

Advantages

Nanotechnology and bioremediation are cost-efficient compared to conventional physical and chemical remediation methods, as they rely on naturally occurring biological processes or nanoscale materials that can be synthesized with relatively low resource input. This affordability makes them feasible for application in large-scale or resource-limited scenarios. Both methods align with principles of environmental sustainability. Bioremediation utilizes microorganisms to detoxify contaminants, ensuring the process is ecologically compatible and non-destructive. Nanotechnology improves bioremediation by producing recyclable materials that break down into non-toxic byproducts, thus reducing the environmental impact. These methods ensure the restoration of soil health, hence long-term ecological balance.

Traditional remediation techniques usually involve harsh chemicals or mechanical disruption, which can lead to residual pollutants or unintended consequences. In contrast, bioremediation mainly relies on natural microbial populations, while nanotechnology allows for targeted treatment of contaminants, minimizing collateral damage. These approaches minimize byproducts that could harm the ecosystem, making them safer and more environmentally friendly alternatives.

Challenges

Another big disadvantage is the fact that remediation takes a considerable amount of time to degrade the contaminants with the help of microbes, especially with recalcitrant or complex ones. Although nanotechnology accelerates reactions in some aspects, it never completely removes time requirements for total microbial degradation and is thus not very suitable for sites requiring quicker action. Another challenge is that bioremediation is site-specific, where the success of these methods largely depends on variables such as the composition of soil, type of contaminant, and environmental factors such as temperature, pH, and moisture content. These require customized solutions to each site, which can take a lot of time and resource.

Survival of microbes in contaminated sites is also a critical concern. Toxic environments, such as the presence of heavy metals, extreme pH levels, or other harsh conditions, can inhibit microbial activity and reproduction, which are crucial for effective bioremediation. Although nanoparticles can create favorable conditions by immobilizing contaminants, they may also pose risks to microbial populations if not carefully designed. Achieving a balance between nanoparticles and microbial activity is essential to maintain their synergistic functionality.

Conclusion

Nanotechnology and bioremediation are transformative approaches to soil remediation. Each of these methods has its strengths and limitations, but their integration holds immense potential for sustainable and effective contamination management. Continued innovation and interdisciplinary collaboration are essential to realize their full potential in addressing global soil contamination challenges.

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