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NANOTECHNOLOGY IN SOIL REMEDIATION: EMERGING INNOVATIONS, MECHANISMS AND CHALLENGES FOR CONTAMINANT REMOVAL

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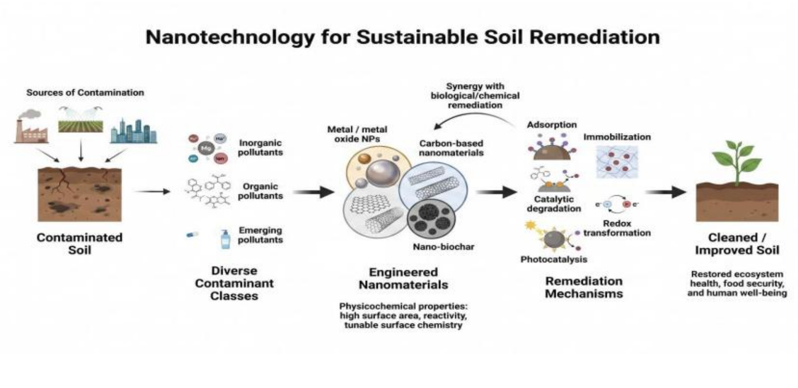
ABSTRACT:
The rate of industrialization, unsustainable farming practices, and rapid urbanization, leading to soil pollution, is a major environmental issue worldwide. It is harmful to the ecosystem and food security, as well as human health. Although traditional remediation techniques are widely used, they may have drawbacks, including costly treatment, lengthy treatment time, and limited effectiveness, as well as in complex soil conditions. Consider the context here, and the interest in using nanotechnology as a new and green soil remediation technology becomes apparent. This article discusses the negative effects that different types of pollutants in soil, such as inorganic, organic, and emergent, have on the environment. The various classes of nanomaterials include nano biochar, carbon-based materials, metal oxide nanoparticles, metal nanoparticles, and metal and metal oxide particles. Additionally, it explores the unique physicochemical characteristics that boost their ability to eliminate pollutants. We offer some of these methods of nano-remediation, such as adsorption, immobilization, catalysis, redox transformation, and photocatalysis. The synergy potential is studied by incorporating nanoparticles with biological and chemical methods for cleanup. All types of production methods, tests and test procedures, environmental risks, and issues with wide adoption are covered in the article. Future perspectives emphasize the importance of developing long-term synthesis processes and comprehensive testing and risk assessment for safe and effective utilization of nanotechnology in soil remediation. With the aid of nanotechnology, soil management choices that are feasible, affordable, and eco-friendly could become possible.

KEYWORDS: Soil contamination, soil remediation, environmental pollution, nanomaterials, and heavy metal adsorption



INTRODUCTION
Food production systems across the world are the subject of growing pressure due to factors including increasing population, poor soil quality, changing weather patterns, and damaging farming practices [1-3]. Among the various environmental issues associated with these factors, soil pollution has emerged as one of the most persistent and complex challenges of the modern industrial era. Soil is now found to be contaminated by many harmful compounds, which have been introduced into the systems due to human activities like rapid urbanization, poor

waste disposal, mining, production of chemicals, and intense farming [4]. These pollutants threaten plant health, ecosystem health, and soil health.

Soil contamination has garnered a lot of attention from scientists in the past 20 years [5]. It's because people are realizing what the impact is in countries such as the economy, agriculture, environment, etc. Over time, it expanded to include not only environmental engineering but also soil and agricultural engineering, as well as applied microbiology [6]. Heavy metal pollution has recently been under scrutiny for many reasons, including the fact that it doesn't break down, is hazardous, and may bioaccumulate in food chains, endangering both humans and the ecosystem in the long run.

Several common methods of removing contaminated soil include excavation, stabilization, phytoremediation, and soil cleansing. These techniques work on some occasions but tend to be costly and labour-intensive, and the degree of effectiveness varies by soil type [4]. Increasing production without aggravating environmental degradation is a critical challenge to increasing food supplies for the current climate of food need and availability. It has become increasingly clear that definitive solutions to remediation problems are needed, which aim to reduce the bioavailability and mobility of contaminants, rather than render them completely innocuous or impossible to find in the environment. These include phytoremediation, biological transformation, electrochemical treatments, and adsorption stabilization. All these have their advantages, but the conditions at the respective sites can affect them [7].

In this case, nanotechnology has proved to be a means of change to remediate polluted environments. As the use of engineered nanomaterials (ENMs) has expanded to various industrial, commercial, and research sectors such as agriculture, health, energy, and environmental studies, they have generated considerable interest within the academic and industrial community [8]. Engineered nanomaterials have unique physicochemical properties that make them effective at removing contaminants from complex environmental matrices, including challenging-to-reach areas. These features include increased reactivity, functional versatility, nanosize, and specific surface area [9]. As nanotechnology expands by creating unique functioning nanoscale structures, devices, and systems that are not available by more traditional methods of cleanup, there is a new range of possibilities in recovering resources and restoring the environment where it has been harmed. The metal oxide nanoparticles (MONPs) and metal nanoparticles (MNPs) are instrumental in facilitating the development of nanotechnology-based remediation. The discovery of metal oxide nanoparticles (MONPs) and metal nanoparticles (MNPs) has significantly accelerated the development of nanotechnology-based remediation. As far as contact with heavy metals and persistent organic pollutants and other pollutants are concerned, these nanomaterials are second to none [10-12]. They are suitable for a wide range of systems, both in and ex situ, in various treatment efficiencies across various environments [13]. These include slurry reactors and immobilised carbon, zeolite and membrane matrices etc. Destructive and potentially remediating technologies that could transform some harmful chemicals with nanotechnology include chlorinated solvents, organochlorine insecticides, and polychlorinated biphenyls (PCBs) [14].

Nutrition, more efficient pesticides and nitrogen delivery are needed for sustainable farming, and these are made possible with the aid of nanotechnology. Nanotechnology has been demonstrated as more effective when applied in addition to biological methods including phytoremediation and microbial remediation, to deal with/remove toxins. In complex soil environments, microbial systems with nanoparticles are combined to enhance degradation and remediation in order to increase the effectiveness of the process [15, 16]. Nanomaterials can regulate the salinity of soil to enhance soil structure, root growth, and growth of plants [17]. Using rhizobacteria, genetic engineering, and chemical alterations are some of the ways that researchers have looked into to make phytoremediation more successful [18]. The good news is this, but it hasn't put to rest concerns over possible risks manufactured nanomaterials pose to soil ecosystems, mobility, and the environment. It is important to understand the interactions of nanoparticles with soil components to guarantee their safe and effective use. The application of nanotechnology matters a lot when pollution takes over the soil. It provides efficient, flexible, and innovative solutions that are effective in the long term. Let's explore today what soil pollution is and how it's categorized; how it is cleaned using nanomaterials; the developments in soil remediation; problems it may cause; and the solutions to soil remediation using nanotechnology.

2. Sources and types of soil contamination

Soil contamination can come from several natural and anthropogenic sources, and it affects agriculture, ecosystems, and human health. With current farming practices, pesticide residues may still be present in the soil even when applied within the legal limit, and this can have infrequent and long-term adverse impacts on soil quality [19, 20]. The extremely rapid process of urbanization and industrialization in metropolitan areas has contributed greatly to soil pollution due to the contamination of heavy metals. The levels of arsenic (As) concentrations and cadmium (Cd) concentrations are high in industrial processes [21]. The copper (Cu), zinc (Zn), and lead (Pb) loads from road traffic increase on the streets of town to urban areas [22].

2.1. Classification of soil contaminants

Soil contaminants can be of natural origin (geogenic) or anthropogenic. Harmful compounds can be liberated into the soil matrix as a natural consequence of geological activity such as earthquakes, volcanic activity, and degradation of parent materials. Natural geochemical processes have been found to deposit perchlorate (ClO_4^-) on dry land [23, 24]. On the contrary, human pollution is primarily the result of human activities such as farming, industries, and improper disposal of waste. These sources can introduce many soil contaminants into the environment, including biological and radioactive contaminants and organic and inorganic contaminants [25, 26]. Both inorganic and organic pollutants are present in soil, and they behave and interact with the environment in different ways [27].

2.1.1. Inorganic Contaminants

Heavy metals and metalloids are the most harmful kind of soil pollutants, as they do not break down and persist in the soil. Examples of heavy metals are cadmium (Cd), lead (Pb), chromium (Cr), mercury (Hg), copper (Cu), and zinc (Zn) [28]. The most appropriate name for arsenic (As) would be a metalloid. The sources for these components are natural weathering conditions, as well as human activities [29]. All of these are known to bioaccumulate in food chains, decrease plant production, disrupt microbial ecosystems, and accumulate in soils, and constitute a major health threat to humans [28, 30].

2.1.2. Organic contaminants

Persistent organic pollutants (POPs) and phthalates (PAEs), polychlorinated biphenyls (PCBs) and BTEX chemicals are the major organochlorine components of soil [31-33]. These pollutants are mainly associated with fossil fuel usage in agriculture, other industrial activities and consumer goods. They have also the biochemical properties of stability and persistence: They can persist in soil and groundwater and bioaccumulate. Neurological, reproductive and cardiovascular systems have all been affected adversely and there are some indications that these chemicals can also lead to cancer [34].

2.2. Emerging contaminants

The complicated behaviour and ecological disruption potential of emerging toxins have made them more important than conventional pollutants. These include for example microplastics, pharmaceuticals, engineered nanomaterials (ENMs) and hydrocarbons from petroleum. The majority of the nanoparticles that are created end up in soil. These particles can be emitted from vehicles, factories, cigarettes and buildings (35, 36). Many studies have demonstrated that microplastics alter the physical, chemical and microbe activity of soil [37, 38]. Besides PAHs and PCBs, they can contain medicines, heavy metals [39-41].

Misuse of pharmaceuticals and irrigation of effluent have resulted in higher detection of pharmaceuticals in soil particularly antibiotics. This changes the microbiota of the soil and induces the resistance of antibiotics [42]. The petroleum-derived hydrocarbons adversely affect soil characteristics like nutrient availability, water retention and soil porosity. They are able to pass via adsorption, leaching, and volatilisation, among other processes [26].

Many physicochemical changes happen in soil-plant systems when engineered nanoparticles are integrated. Adsorption, desorption, precipitation and dissolution reaction are some of the Changes which wear particles face as they are introduced in soil-plant system. All of these processes impact their toxicity, bioavailability and mobility. They are reportedly toxic for soil microorganisms and plant due to their ability to cause oxidative stress [29].

2.3. Sources and Distribution of heavy metals

As well as being sources of pollutants, soils can contain heavy metals, such as arsenic, nickel or lead, as a source [43]. These metals are sources from the earth (geogenic) and from man (anthropogenic) and there are 2 main locations. All of these are regarded as natural sources [44] from weathering of the parent rocks, the air deposition in response to volcanic emissions and wind erosion. Human activities are primarily responsible, such as mining, manufacturing or agricultural inputs or urbanisation, with the majority of these mostly to blame [45].

Most non-pollutants of soil metals are industrial facilities, agriculture supplies (insecticides and fertilizers) and consumer products such as batteries and paints [44]. In very few smelting facilities and industrial areas, there are heavy metal contents, which could rise to the dangerous range [46]. Transportation operations lead to release of metals in the soil in close vicinity to the highways as a result of multiple factors: fuel combustion, decay of tyres, equipment corrosion [47].

As a result of atmospheric deposition and human activities, heavy metal concentrations tend to be greater in the top layers of soil profiles [48, 49]. These pollutants can harm soil biodiversity in a variety of ways, such as reducing microbial activity, altering soil animal populations, and disrupting ecological processes [50]. This includes the ability of earthworms to uptake, accumulate and transport the heavy metals such as cadmium, copper, lead and zinc over soil ecosystems [51].

3. Types of nanomaterials for soil remediation

The advent of nanotechnology as a disruptive technology has provided more effective and targeted solutions for minimizing the contamination of agricultural soils in an environmentally- friendly manner [52]. In recent years, the application of nanotechnology as a cure-all for the diversity and complexity of polluted soils has increasingly come to the fore [53]. Any substance having a dimension in the nanoscale range (1-100 nm) is considered a nanomaterial [54]. They have very unique chemical and physical properties, including: A large specific surface area, Increased chemical and physical reactivity, high adsorption capacity. These properties enable them to take up, transform and breakdown many pollutants in soils [55].

3.1. Iron based nanoparticle

The high activity and adsorption capability of iron-based nanoparticles has led to their significant focus in the field of soil remediation [56] especially zero-valent iron (nZVI) (Fig. 1). The ability of nZVI particles to effectively reduce and immobilise a wide range of contaminants, such as radionuclides, heavy metals, chlorinated organic compounds, is just a few of a long list of contaminants they will handle. The small volume and high activity of nZVI particles result in a high chemical reactivity and mobility in the soil, making them suitable for in-situ soil remediation processes [58].

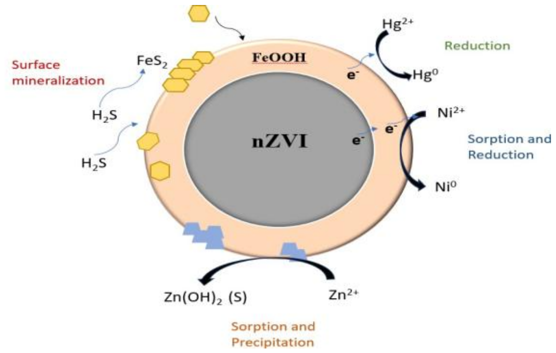


Fig. 1 Mechanistic Pathways of Contaminant Removal by Nanoscale Zero-Valent Iron (nZVI) in Soil Systems

Table 1 Comprehensive Framework for the Classification of Soil Contaminants: Sources, Chemical Characteristics and Ecotoxicological Implications

Category	**Type of Contaminant**	**Major Sources**	**Examples**	**Environmental & Health Impacts**	**Reference**
Inorganic Contaminants	Heavy metals & metalloids	Mining, industrial discharge, fertilizers, traffic emissions	Cd, Pb, Cr, Hg, As, Cu, Zn	Toxic to plants and microbes, bioaccumulation in food chain, carcinogenic effects, reduced soil fertility	[59, 60]
Organic Contaminants	Persistent organic pollutants (POPs)	Agriculture, fossil fuel combustion, industrial processes	OCPs, PCBs, PAEs, PAHs, BTEX,	Hormonal disruption, cancer, neurotoxicity, long-term environmental persistence	[61, 62]
Emerging Contaminants	Microplastics	Plastic waste, agricultural films, urban runoff	MPs	Alter soil structure, affect microbial activity, act as carriers for pollutants	[39, 63]
	Engineered nanomaterials (ENMs)	Industrial applications, combustion processes, nanotech products	CNTs, quantum dots, metal NPs	Unknown long-term toxicity, oxidative stress in plants, mobility in soil-water systems	[64, 65]
	Pharmaceuticals	Wastewater irrigation, improper disposal	Antibiotics, PPCPs	Antibiotic resistance, disruption of soil microbiota	[66]

	Petroleum hydrocarbons	Oil spills, fuel leakage, industrial waste	Hydrocarbons, diesel residues	Reduced soil porosity, toxicity to plants, groundwater contamination	[67]
Natural Sources	Geogenic contaminants	Weathering of rocks, volcanic activity	As, Ni, heavy metals	Natural accumulation, long-term soil contamination	[68, 69]
Anthropogenic Sources	Human-induced pollutants	Agriculture, industry, urbanization, waste disposal	Pesticides, fertilizers, metals	Soil degradation, ecosystem imbalance, health risks	[70, 71]

3.2. Carbonaceous nanomaterials

With a large surface area and high adsorption capacity, carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene, have captured the interest in the field [72, 73]. Hollow tubular geometry and high specific surface area of carbon nanotubes (CNTs) allow them to be effective adsorbents for various contaminants, such as heavy metals and organic pollutants [65] (Fig. 2). The adsorption capacities of the 2D carbon nanomaterial graphene are greater [74] than others, including their π-π interaction with aromatic contaminations and large surface area. Furthermore, with an initial concentration of 10mg L-1 the results indicated achieved a noteworthy maximum removal efficiency of 91.71% within 120 minutes [73].

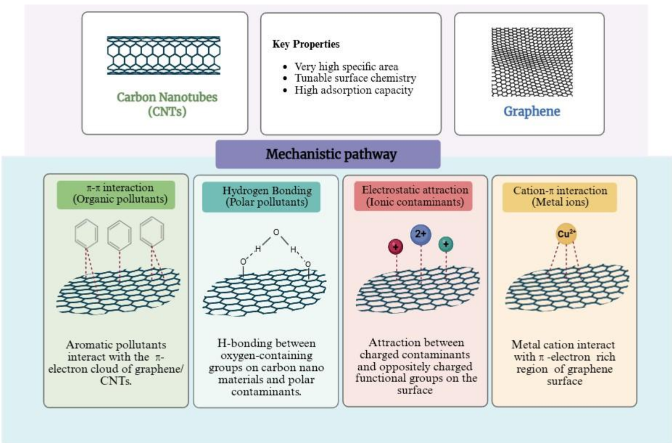


Fig. 2 Mechanistic pathways of contaminant removal by carbon-based nanomaterials. CNTs and graphene provide high specific surface area and tunable surface chemistry, enabling efficient contaminant adsorption. Organic pollutants are retained through π–π interactions and hydrogen bonding, while ionic contaminant undergo electrostatic attraction and metal-ion interaction with the carbon surface.

3.3. Engineered Metal Oxide Nanoparticles

The possibility of using metal oxide nanoparticles for soil remediation has been investigated [75, 76]. These are known as the nanoparticles such as titanium dioxide (TiO2), zinc oxide (ZnO) and manganese oxide (MnO). These nanoparticles have photocatalytic property and can decompose organic contaminations when exposed to light [77]. Moreover, metal oxide nanoparticles can be used to immobilize heavy metals and to adsorb them due to the exchange and surface complexation [78].

4. Mechanisms and applications

Soil pollution and degradation are a major concern for the ecosystems in the world. Unique physicochemical properties of nanomaterials have proven to be highly effective when dealing with contaminants, their degradation and enhancement of their functions. Given this, they may be an alternative means of contaminated soil cleanup [79]. This section emphasizes the main mechanisms through which nanomaterials abate contaminants and enhance function, and elaborates on these in subsequent sections.

4.1. Contaminant removal techniques

4.1.1. Adsorption and Immobilization

The very high specific surface area of nanomaterials makes them efficient in the binding of the heavy metal ions (Table 3) [80]. A physical adsorption, electrostatic, and a mechanism of action are described.

Table 2 Adsorption Properties of Carbonaceous Nanomaterials for Soil Remediation

Nanomaterial	Contaminant	Contaminant Type	Adsorption Capacity (mg/g)	Primary Interaction Mechanism	Remarks	Reference
CNTs (Carbon Nanotubes)	Lead (Pb)	Heavy metal	100-200	Electrostatic attraction, surface complexation	High affinity for divalent metals	[81]
CNTs	Phenanthrene	PAH (organic)	50-100	π-π interactions, hydrophobic interactions	Effective for aromatic hydrocarbons	[81]
Graphene	Cadmium (Cd)	Heavy metal	200-300	Surface complexation, electrostatic attraction	Very high adsorption due to large surface area	[81]
Graphene	Naphthalene	PAH (organic)	80-120	π-π stacking, van der Waals forces	Strong affinity for aromatic compounds	[82, 83]
Graphene Oxide (GO)	Lead (Pb)	Heavy metal	150-250	Oxygen functional group binding (-OH, -COOH)	Enhanced adsorption via functional groups	[84]
Graphene Oxide (GO)	Tetracycline	Antibiotic	120-180	Hydrogen bonding, π-π interactions	Effective for pharmaceutical pollutants	[85]
Multi-walled CNTs (MWCNTs)	Chromium (Cr^{6+})	Heavy metal	90-160	Redox reaction + adsorption	Can reduce Cr^{6+} to less toxic Cr^{3+}	[81]

Fullerene (C60)	Benzene	VOC	70-110	Hydrophobic interaction	Moderate adsorption efficiency	[86]
Nano-biochar	Cadmium (Cd)	Heavy metal	150-300	Ion exchange, surface complexation	Eco-friendly and cost-effective	[87, 88]
Nano-biochar	Atrazine	Herbicide	100-200	π-π interaction, pore diffusion	Good for agricultural pollutants	[62]

Heavy metals and organic pollutants could be eliminated by the adsorption and complexation, cation exchange, chemical precipitation, and cation-π interactions as a remediation method [89]. The power of reduction can be used to remove most of the heavy metals which are able to be reduced and immobilized by the nano zero valent iron/biochar particles (nZVI/BC) [90, 91]. The surfaces of carbon-based nanomaterials are often numbered with other functional groups such as hydroxyl groups (-OH) and carboxyl groups (-COOH). Such groups can interact chemically with heavy metal ions, thus sequestrating them by physical adsorption, charge transfer or ion exchange [73, 92]. Biochar based NCS are obtained by incorporating nanomaterials into the matrices of biochar [93]. Physical adsorption, electrostatic interactions, coprecipitation, complexation, and ion exchange are just a few of the many processes that these composites make possible for the immobilisation of heavy metals [94]. The biochar composite nanomaterials lowering the electrostatic attraction of biochar could be used to be able to release heavy metal ions. The composite nanomaterials of biochar reduced electrostatic interaction between biochar and heavy metal ions was found to be successful method to release the heavy metal ions in the future [95].

Table 3 Adsorption Mechanisms and Kinetics of Nanomaterials in Soil Remediation

Nanomaterial	**Primary Interactions**	**Kinetics Model**	**Evidence & Capacity**
Nano-biochar	Electrostatic attraction, surface complexation	Pseudo-second-order	FTIR shifts; Cd^{2+} ≈ 378 mmol/kg
CNTs / Graphene	π-π stacking, van der Waals forces	Langmuir isotherm	Pb/Cd: 100-300 mg/g
nZVI	Reactive surface sites, electron transfer	Pseudo-second-order	Rapid equilibrium (~120 min)
Metal oxides	Surface binding, adsorption	Intraparticle diffusion	Heavy metal binding confirmed via FTIR

[96] Wheat straw-based Biochar with MOFs for further functionalisation. When MIL-100(Fe) was added to the biochar, the material's specific surface area was increased by six-fold to 419 m2g−1, creating an ability to adsorb heavy metals in soil of triple the original of the biochar, 142 mmol·kg−1 of Cu2+ and 156 mmol·kg−1 of Pb2+ [96]. Carbon nanotubes (CNTs) such as multi-walled carbon nanotubes (MWCNTs) can be used to efficiently immobilise and stabilise heavy metals [97]. In a recent study, a low concentration of multi-walled carbon nanotubes (MWCNTs) has been found to be an efficient and effective tool for reducing the mobility and bioavailability of heavy metals in soil [98]. The surface modification process results into an increase of the adsorbent specific surface area (SSA) as pointed out by Pandey et al. [99] and the additional functional groups help in the chemisorption of heavy metals through electrostatic interactions, chelation, complexation etc. Liu et

al., reported that out of all the three types of biochars, the KRBC is the most effective material for soil remediation from Zn-contaminated soil as it employs higher specific surface area, more surface functional groups and higher aromaticity than other two types of biochars, the RBC and HRBC [100]. The use of biochar modified with these nanoparticles has been found to be effective in binding both arsenic (As) and cadmium (Cd) simultaneously when it is biochar from rice husks, wheat husks, maize, rice, sawdust, and wood chips. Immobilisation of As is mostly accomplished by ligand exchange, whereas Cd fixation is primarily accomplished through ion exchange. The effectiveness of remediation was very closely correlated with the surface hydroxyl groups, the presence of iron oxide phases, and Fe_3O_4.

A new composite material called P-FH@BC, which is doped with phosphorus, was created by Li et al. [22]. There were better immobilization and passivation effects of the Pb(II) and cerium (Ce) contamination in soils. Careful consideration of the application dose, economic feasibility, and environmental sustainability of soil rehabilitation when handling heavy-metal-polluted soils is required to enhance the effectiveness of soil rehabilitation [65]. The possibilities that nanomaterials can bring to this are new and exciting. These novel nanoparticles not only emphasize environmental sustainability and recyclability but also enhance the cleaning efficiency [22]. Another possible advantage to the use of magnetic nanoparticles as remediation agents over traditional remediation agents is that an external magnetic field can easily be pulled them back out of treated systems after they have been used. This allows them to be potentially reused [102]. Their small-size effect and interfacial effect, combined with the bigger surface impact give them the capability to adsorb and immobilizes heavy metals [103]. The composite adsorbent, named as UiO-66-Fe3O4 composite, developed by Wang et al., [104] has excellent magnetic property and large specific surface area, and it can be used as an ideal adsorbent for the metal-EDTA complexes. The identification of zirconium-oxygen coordination as the strongest mechanism involved in adsorption allowed the development of a simple and low cost method for metals recovery [104, 105].

Cellulose nanostructures have great versatility in terms of the covalent chemistry that may be used to modify their surfaces and the ability to change their shape (malleability) into a wide variety of forms while preserving critical properties making them ideal templates. Due to their biodegradability and high synthetic degree, more and more applications have appeared in the environmental field [107]. In order to remediate soils polluted with hexavalent chromium [Cr(VI)] [108], Huang et al. created a composite material called CMC-nZVI@BC, which is nano zero-valent iron supported on biochar. Soil leachability and bioavailability of Cr(VI) were both decreased as a result of its improved immobilisation [109]. The optimal doses, environmental risk, and potential toxicity of these new composites used for soil bioremediation has yet to be assessed, as very little empirical data pertaining to soil bioremediation practice of these composite materials exist [110].

4.1.2. Degenerative catalysis

The concentration of pesticides, hydrocarbons produced from petroleum, PAHs, and other industrial chemicals, along with the accumulation, results in soil contamination by organic pollutants, a large concern for the environment all over the world [111]. Visible-light photocatalytic degradation can be used to effectively remove the organic contaminants, and there are efficient methods for remediation of contaminated soils, which include adsorption and photocatalytic reduction of metal ions that allow there in-situ immobilisation [112]. Photocatalytic degradation, shown to be the most effective method, is the process to be used for treating the low levels of organic pollutants [84]. There are two potential pathways for the photo-oxidation of organic pollutants presented in tables 4 and 5 [113]. Organic pollutants can be directly photodegraded by visible light, after the pollutants have been catalysed into an excited triplet state. Then, the electrons move into the conduction band of the nanoparticles and form "radical cations" [114]. When the dissolved oxygen is able to oxidize the organic molecule via the formation of the superoxide anion radical, hydroxyl radical will also be generated, making the process of oxidation much easier [115]. The hydroxyl radicals they form on the surface of the photocatalyst generate electron-hole pairs and excite the VB electrons with energies equivalent to or greater than the energy of the incident photons, generating the indirect degradation pathway [116]. The decay rate is a function of the stability and molecular structure of the objects under decay [117]. Eventually, these molecules will be mineralised.

Table 4 Gradation Mechanisms of Nanomaterials in Soil Remediation

Nanomaterial	**Degradation Process**	**Target Contaminants**	**Efficiency**
S-nZVI	Redox transformation → CdS precipitation	Cd, heavy metals	~96-98% removal
Biochar-metal oxide nanocomposites (BNC)	Surface catalysis	Organic pollutants, dyes	~98.6% efficiency
Functionalized biochar (BC-MO)	Photocatalytic degradation	Persistent organics	Accelerated degradation rates

The unique characteristics of the electric, chemical and physical properties of carbon-based nanostructures have been reported [118]. Multi-walled and single-walled carbon nanotubes (SWCNTs) potentially can remove both organic and inorganic pollutants, while graphene can serve as an adsorbent or as a functional part of photocatalytic composites [119, 120]. The carbon-based nanomaterials can be possible photocatalysts and the functionality of the materials could be further enhanced by the functionalisation or by the addition of additional elements [84, 121]. In combination with the clays, hybrid materials can be obtained which have higher mechanical strength (Fig. 3). These nanocomposites possess higher molecular loading capacity and more controlled release behaviour when compared to pristine clays and are more efficient as a contaminant removal technology in wastewater. They do a particularly good job at removing per- and poly-fluoroalkyl substances (PFAS) [122, 123]. The material called "Biochar-nano zero-Bivalent iron" (BC-nZVI) is an innovative, new material for environmental remediation, which makes nano zero-valent iron more stable and more reactive and selective in the process of environmental cleaning. The first components that Toghan et al. investigated in the composite film were polyvinyl alcohol, polyaniline and carboxylated graphene oxide, which proved to be successful for the removal of either the dye or antibiotic, in the case of dye removal or antibiotic removal respectively, from wastewater respectively [125].

Table 5 Catalytic Nanomaterials: Mechanisms, Targets and Efficiencies

Catalyst	Primary Mechanism	Target Pollutant	Efficiency
Fe_3O_4/FeS_2 biochar	Electron transfer (redox)	Pb^{2+}, Ni^{2+}	2-3× faster removal
TiO_2/g-C_3N_4/CeO_2	Z-scheme photocatalysis	Tetracycline	>90% degradation
P/EDTA-biochar	Pore diffusion + catalysis	Organic pollutants	~95% mineralization

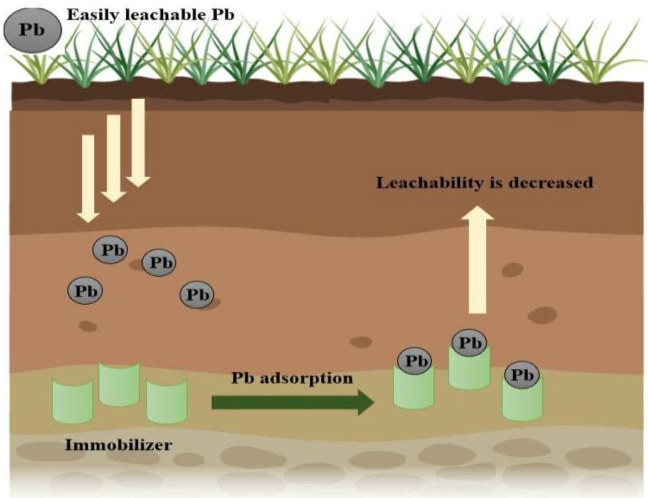


Fig. 3 Adsorptive Immobilization of Lead (Pb) in Soil for Environmental Remediation

Metal oxide nanostructures, such as, Fe3O4 and TiO2, generate Reactive Oxygen Species (ROS), including hydroxyl radicals (·OH), through some processes such as Fenton reaction, photocatalysis and electrocatalysis. This in turn reduces the size of the organic pollutants into smaller less harmful molecules [126]. Rhodamine B (Rh.Alternatively, B) can be degraded using inorganic metal nanoparticles (mNPs) as catalysts, in contaminated water [127]. Emulsion liquid membranes (ELMs) have been combined with nano-zero-valent iron (nZVI) and the combined catalyst has been proven to be more effective in enhancing the catalytic activity towards the oxidative degradation of organic solvents in aqueous systems [128]. An enhancement in the photocatalytic activity of ZnO can be obtained by suppressing the recombination process of the photogenerated charge carriers, one method of modification is by inserting with Ag nanoparticles. Several pollutants using photocatalytic materials (after silver treatment) have been successfully reduced such as tetracycline, phenol and polychlorinated biphenyls (PCBs) [129]. CeO_2 based nanoparticles (NPs) can be doped with different metal ions to enhance their surface reactivity for better degradation of organic compounds like dyes, phenols, amines and aromatic nitro compounds [130]. An increase in photocatalytic efficiency and better charge separation both brought about by doping, which causes oxygen vacancies to develop [131]. To address these challenges, scientists at the Laboratory of Photofunction, Alamelu et al., developed a highly dispersed sulfonated graphene nanosheets with Ag and TiO_2 nanoparticles and abbreviated it as SGT-Ag. They then demonstrated the ability of those nanosheets to degrade water-soluble positively charged dye -Rh.It has been found to be highly photocatalytic in the presence of B, anionic dye methyl orange, and 4-nitrophenol under sun-light conditions [132]. Organic pollutants include personal care products, antibiotics, dyes, insecticides and phenols. Nanoparticles can carry enzymes which are very effective at breaking down these toxins [133]. Enclosed at the nanoscale, enzymes are much more stable, operate longer and are more resilient to varying pH and temperature [134]. Cellulose nanocrystals (CNCs) are an excellent option for removal of dyes from membrane systems or for use as stabilising supports in catalysts for the degradation of organic contaminants [135]. While the use of these compounds for soil remediation is still limited, further research is essential to determine the effectiveness, practicality and environmental safety of these substances.

4.2. Enhanced Nutrient Delivery and Soil Health Management

The world's growing population puts agriculture under increasing stress both in terms of productivity and food security. Biotic factors like infections caused by pathogens such as bacteria and fungi, and abiotic factors such as drought and salt also impact yields [136]. In order to reduce crop losses and negative environmental consequences, agricultural management uses a variety of measures [137]. One of the most promising and eco-friendly ways to reduce agricultural losses is via the use of exogenous protectants and nanotechnology [138]. The nanoparticles of metals such as gold, silver, zinc oxide (ZnO) and titanium dioxide (TiO2) could potentially be incorporated into pesticides or fungicides and fertilisers to improve soil fertility, productivity and resistance to biotic and abiotic stresses [139].

4.2.1. Nano-fertilizers

Conventional fertilizers such as urea may lose large amounts of their nutrient content, up to 40-70%, from the soil after they are applied through leaching, volatilization, and surface run-off [140]. Nano-fertilizers, due to their ability to supply the plants with a controlled dose of plant nutrients, to gradual release of plant nutrients over a long period of time, and to continuous supply of basic plant nutrients to plants, are an efficient and sustainable approach to crop nutrition [141]. The use of nano-fertilizer may be able to provide approximately 20% higher crop production as compared to conventional fertilizers and a 30% increase in nutrient-use efficiency (NUE) [142]. Slow-release nano-fertilizers (SRNFs) and controlled-release nano-fertilizers (CRNFs) facilitate efficient nutrient delivery, e.g., via targeted/nanoscale transport, nutrient encapsulations for controlled release, and incorporation into organic biopolymer matrices [143]. Release from SRNFs is slower than for conventional nanoparticles. Li et al.., developed a novel PVA/ST-Zn-BSRF, a type of slow-release fertilizer with polyvinyl alcohol/starch (PVA/ST). Field trials showed that PVA/ST-Zn-BSRF could improve the yield of wheat by as much as 87.5%, as well as the amount of organic matter in the soil and its stability [145]. Field trials revealed that PVA/ST-Zn-BSRF had the potential to enhance wheat yield up to 87.5%, soil organic matter content, and stability [145]. Maduwanthi et al. developed nanohybrid materials by incorporating nanoparticles (NPs) into the matrix of sodium alginate and carboxymethyl cellulose and cross-linked it with Ca^{2+} using ultrasonication [146]. The slow-release fertilizer was significantly more effective than conventional NPK application in the controlled environment in elevating harvests [146]. Sharma et al. developed a nano-fertilizer by integrating copper with salicylic acid (SA) in a chitosan solution for slow and persistent efficacy in plants [147]. The formulation of controlled-release nano-fertilizers (CRNFs) is linked to coating materials that slow the rate at which nutrients are released, thus providing a more consistent and regulated nutrient release [96]. Timilsina et al. observed that the ripening of papaya fruit was successfully inhibited by the collective effect of silver (Ag) and chitosan (ZnO) nanoparticles, which affected the total soluble solids (TSS) and total titratable acidity (TTA) changes in the fruit [148]. The fruit firmness and physiological loss in weight of treated fruits were greater than those of the control.

Tay et al. successfully demonstrated the continuous urea release from cellulose nanoparticles (CNPs) made from waste paper [149]. The release occurred under different environmental conditions, including periodically irrigated soil and watery conditions. AP) and amorphous calcium phosphate (ACP), for use as urea (NH_4HPO_4)-loaded nano-fertilizers. The Nitrogen and Phosphorus could be released under control. ACP-urea significantly enhanced the yield of dry biomass and relative chlorophyll content in greenhouse tests with Zea mays (maize) [150]. Latha et al., designed fertilizers (Lignorea) comprising of NP sources with a matrix of chitosan and spherical lignin nanoparticles (LNPs) along with suitable cross-linkers.

These N-fertilized Nano-fertilizers released 30-35% nitrogen to soil for 15 days which enabled the controlled nitrogen fixation and release [152-154].

Nano-fertilizers are more effective than conventional fertilisers as they reduce the environmental adverse effects, yield more and the application rate is controlled. If carefully applied, however, phytotoxicity is not expected to be a concern [155]. Correct application rates, possible toxicity and long-term impacts on the ecology of the plants remain to be studied in more detail [156, 157].

4.2.2. Nanomaterial induced enhancement of soil physical properties and microbial activity

Nanomaterials are used for the removal of contaminants from polluted soils due to their high reactivity, mobility and function [17]. Soil systems can be affected by alterations in nanomaterial interactions with inorganic and organic ligands that lead to changes in pore structure, water dynamics, aggregate stability and microbial activity (Fig. 4). With their very small size, nanomaterials can penetrate these soil micropores and impact the connectivity, porosity and overall structure of the soil [158]. Nano-biochar improves soil properties such as soil quality, water-holding capacity and nutrient-holding capacity [159]. Nepal et al., [161] have demonstrated that carbon nanoparticles are an effective method for reducing nutrient leaching losses in soil that has a coarse texture. Ngo et al., reported that the water-absorption capacity of cellulose nanofibers (CNFs) was attributed to the hydrophilic nature of their functional groups and special structure. There was a 98% increase in soil water content when 1% CNF was added [162]. Wet CNFs have an ability to bind soil particles and promote the formation of macroaggregates by at least 48% in Massa soil and 59% in paddy soil [163]. Population changes of soil microbes result from input of nanoparticle populations [164]. In soil, nanomaterials have far-reaching impacts on microbial communities, changing their diversity, biomass, community makeup, and overall structure [165]. To reduce soil microbial biomass carbon (MBC) and increase microbial diversity, Zuo et al., showed in a meta-analysis that

CNM exposure drastically reduces MBC [166]. The pot trials experienced by Udomkun et al., [167] on black bean demonstrated significant enhancement in soil pH, soil moisture content (MC) and soil organic carbon (SOC) upon application of the nano Biochar (NBC). After 6-weeks, using 1% and 3% of NBC in soil explained the increase in SOC level and diversity of N-fixing bacteria (NFB), abundance of phosphate-solubilizing bacteria (PSB) and total plate count (TPC) [168]. But most of the present research is conducted under pure culture circumstances [9, 169] using single-strain methods. Due to the many challenges faced in the field, evaluation is typically more difficult. When the proper type and level of nanomaterials agents are applied, soil microbes could be important to ecosystem function, nutrient cycling, organic matter decomposition and soil fertility.

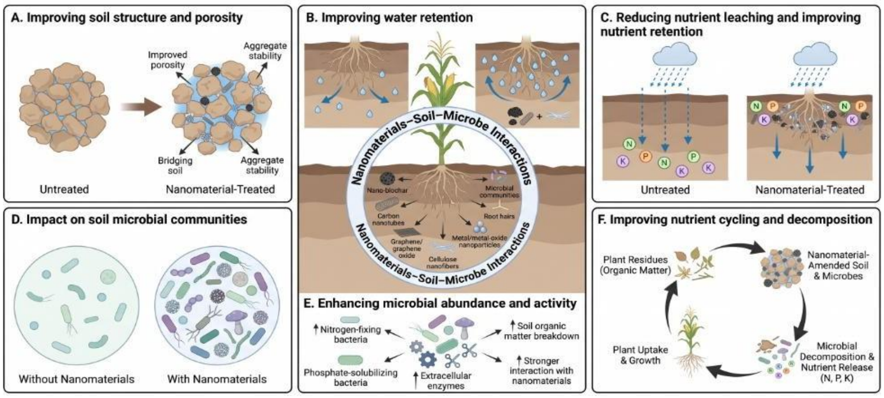


Fig. 4 Role of nanomaterials in improving soil structure, water retention, and microbial activity. (A–C) Nanomaterials modify soil porosity and aggregate stability, enhance water retention, and reduce nutrient leaching while improving nutrient availability in the rhizosphere. (D-F) Nanomaterial soil microbe interactions enhance microbial abundance and activity, accelerate organic matter decomposition and nutrient cycling, ultimately supporting plant growth and overall soil health.

5. Integration of other techniques with remediation

The use of nanomaterials, along with other methods used for remediation, could enhance the process's overall effectiveness and durability [170]. The chemical oxidation, bioremediation and phytoremediation, when coupled with nanomaterials, might be able to address limitations of the individual technologies while also providing a synergistic effect [171].

5.1. Nanomaterials and bioremediation

The use of microorganisms to reformulate or degrade soil contaminants is bioremediation. The advantage of incorporating nanoparticles in bioremediation includes that contaminants may be made more bioavailable, more electron acceptors or donors can also be provided, degradation microorganisms may be more viable and functionalised [66]. An electron donor effect may be useful in that the nZVI particles may facilitate reductive dechlorination of chlorinated organic compounds and thus enhance the growth of anaerobic bacteria [172] (Fig 5).

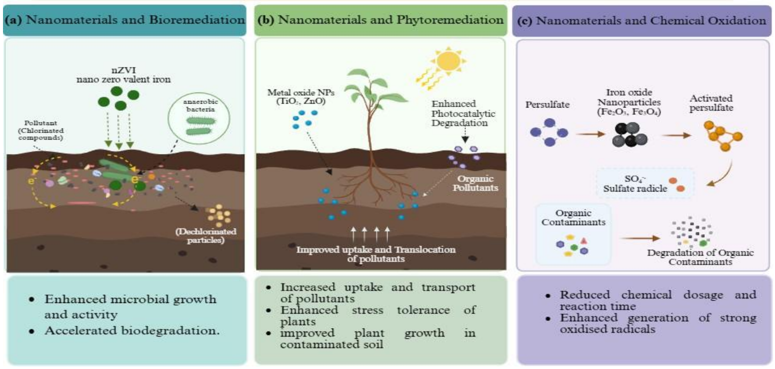
5.2. Nanomaterials and Phytoremediation

Plants are used in phytoremediation to eliminate, accumulate, or break down contaminants in soil [173]. Nanotechnology can enhance the ability of plants to either absorb or move contaminants, which could accelerate the process of phytoremediation. The use of metal oxides would be advantageous in the application of photocatalytic degradation of organic contaminants on soil or plant foliar surfaces treated with metal oxide nanoparticles (MONPs),
e.g. TiO or ZnO [171, 174]. Furthermore, the stress tolerance and growth can be improved in plants when they are planted into polluted soil by nanomaterials.

5.3. Nanotechnology enabled chemical oxidation for soil remediation

The process of chemical oxidation can be used to break down and transform soil organic pollutants by utilizing strong oxidising agents such as persulfate and hydrogen peroxide [175] to clean the soil. An innovation that could greatly enhance the efficiency of chemical oxidation processes would be to use catalysts composed of nanomaterials. To illustrate, iron oxide nanoparticles have the ability to activate persulfate, resulting in the production of sulphate radicals. These radicals could decompose soluble organics, and are powerful oxidizing agents [176].

Fig. 5 Integration of nanomaterials with conventional soil remediation techniques. (a) Nanomaterials



combined with bioremediation enhance microbial activity and accelerate contaminant biodegradation. (b) Nanomaterials integrated with phytoremediation improve pollutant uptake, translocation, stress tolerance, and plant growth. (c) Nanomaterials coupled with chemical oxidation enhance reactive species generation, enabling efficient degradation of organic contaminants with reduced chemical dosage.

6. Synthesis and characterization of nanomaterials

6.1. Synthesis of nanomaterials

Chemical reduction, sol-gel and hydrothermal synthesis and green synthesis are some of the widely used techniques for synthesizing soil-cleaning nanoparticles [177]. One common way of synthesizing the metal nanoparticles, such as the nZVI, is by a chemical reduction process [178] a process where a reducing agent turns the metal ion to elemental state. For the purpose of creating metal oxide nanoparticles, the sol-gel and hydrothermal processes are often used. These techniques can be used to control the particle size and the shape of particles [179] (Fig. 6). Green synthesis methods have become increasingly popular recently, due to their low prices and the positive effect on the environment [180]. All these techniques are based on plant extracts or microorganisms as reducing and stabilising agents. The low production cost plays an important role in making them sustainable and with this property, these Nanomaterials produced by green synthesis can be used in soil remediation.

6.1.1. Reduced manufacturing costs:

Renewable, readily available, low cost materials like plant extracts or microorganisms, are commonly employed in green synthesis processes as reducing and stabilising agents. This renders the overall manufacture of nanomaterials to be relatively inexpensive, as opposed to conventional chemical synthesis techniques which require expensive synthesis equipment as well as expensive reagents. The reduced costs of manufacturing nanoparticles have improved access to and economic feasibility of using them on large-scale soil remediation projects.

6.1.2. Diminished environmental impact:

Using green synthesis techniques, using renewable and natural resources, is one way of reducing the environmental impact of making nanomaterials. Another approach, chemical synthesis procedures, on the other hand, might require the employment of harmful chemicals and generate toxic waste. By reducing the negative impact on the environment, green synthesis is in line with sustainability principles and makes nanomaterial production more eco-friendly.

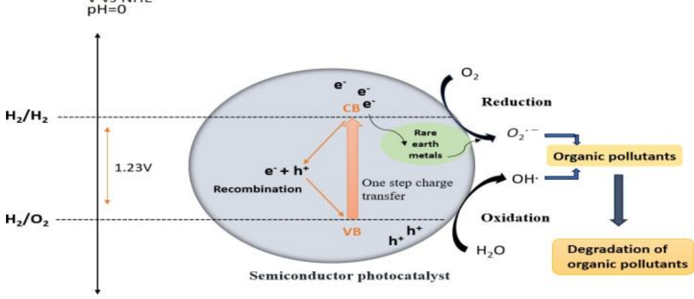


Fig. 6 Photocatalytic Degradation of Organic Contaminants via Rare Earth Metal-Modified Semiconductors.

6.1.3. Potential for local production:

Easy availability of natural resources for the synthesis of plant extracts for sustainable production of nanomaterials could be a possibility for local manufacturing near contaminated areas. This decentralized approach to manufacturing helps lower transportation expenses and emissions, further enhancing the sustainability of the cleaning process. Increased engagement of local stakeholders in remediation improves the empowerment and involvement of the local population in the remediation process.

6.2. Increased adoption and implementation

If the green synthesised nanomaterials are using less the remediation methods based on nanotechnology will receive more acceptance and usage. As the cost of these longer-term clean-up strategies decreases and the environmental impacts are being realized, more and more Governments, business and communities might sign up for and do such a long-term clean-up.

6.3 . Characterization Techniques

Nanoparticles properties and effectiveness in soil remediation can only be understood via their characterisation. Brunauer-Emmett-Teller (BET) surface area analysis, X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared (FTIR) analysis are some of the many techniques used for examining nanomaterials [181]. The crystal structure and phase composition can be determined using XRD, while the size, shape and morphology of nanoparticles can be determined using TEM and SEM [41].

7. Environmental risks and responsible application

Although the various possibilities of soil remediation by nanoparticles is interesting, the possible environmental effects of such technology should not be overlooked [180]. Nanomaterials can be toxic and bioaccumulated by non-target organisms when they are released to the environment and present certain issues. When using these nanoparticles to clean up soils, precautions and management need to be taken to minimize risks [41]. Biodegradable nanomaterials (BM), including nanobacteria and nanoparticles produced in an ecologically friendly way, could reduce the long-term negative effects on the environment. Second, controls are that Nanomaterials should be used in a manner that reduces the impact on the environment. This may be by using stabilised nanoparticles or by integrating them into existing material with good level of environmental protection. Complete soil monitoring and risk assessment approaches are needed to better understand the behaviour, movement, and possible impact from nanomaterials in soil [182]. Environmental transformation processes largely influence transformations of nanoparticles (NPs) that affect their physical, chemical and biological properties and the particle's mobility, toxicity and stability [183]. This involves looking into how soil microbes interact with soil components such as organic matter and clay minerals, and how this relates to the behaviour of nanomaterials in the soil. To determine the durability and effectiveness of the nanomaterials utilised, it is essential to monitor the treated areas for an extended period of time [171]. The cost effectiveness of performing green synthesis techniques for the manufacturing of nanomaterials is one of the important features that makes nanomaterials to be more widely used in soil remediation and enhances their sustainability.

7.1. Reduced manufacturing expenses: Sometimes renewable and easily available resources (plant extracts, microorganisms) can be used as stabilising and reducing agents in green synthesis methods, thus minimizing production costs. It offers a lower cost in nanomaterial manufacturing because compare to the traditional chemical synthesis methods that require expensive reagents and equipment. The production of nanoparticles is now more cost-effective and available to large soil remediation works.

7.2. Diminished environmental impact: Green synthesis approach minimises the environmental impact of the manufacturing of nanomaterials by utilising natural and renewable resources. Chemical synthesis procedures, on the other hand, could use dangerous chemicals and result in toxic waste. By reducing the negative impact on the environment, green synthesis is in line with sustainability principles and makes nanomaterial production more eco-friendly.

7.3. Potential for local production: Close to contaminated areas, synthesis of nanomaterials on-site may be easier due to possible plant extracts and other ingredients for green synthetic processes. This decentralised manufacturing approach also lowers transport costs and emissions, leading to a more sustainable cleaning process. Local production allows communities to get involved and self-determine, as local stakeholders have the chance to be involved in cleanup operations (Fig. 7).

7.4. Enhanced adoption and execution: The ease of acquiring green synthesized nanomaterials in an eco-friendly and affordable way, could lead to its preferred use in soil remediation. As costs are reduced and the benefits to the environment increase, more stakeholders, including governments, businesses and communities, may be interested in and willing to participate in and implement these long-term remediation projects.

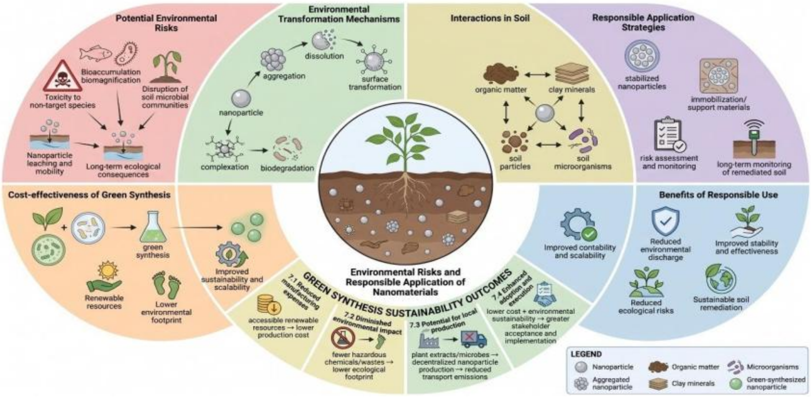


Fig. 7 Environmental risks and responsible application of nanomaterials in soil remediation. Nanomaterials may undergo aggregation, dissolution, surface transformation, complexation, and biodegradation while interacting with soil constituents, microorganisms, and plants, potentially affecting mobility, bioavailability, and toxicity. Responsible application through stabilized or supported nanoparticles, risk assessment, long term monitoring, and green synthesis can reduce environmental risks while improving cost-effectiveness, sustainability, local production, and adoption of nanotechnology-based remediation.

8. Recent advances

In the past few years, numerous synthetic nanomaterials have been created and produced to be applied in soil remediation. These are carbonaceous nanoparticles, metallic/metallic oxide nanomaterials and polymeric nanocomposites. They decompose pollutants through adsorption, redox processes and photodegradation [184]. It is noteworthy to mention that 'nano-phytoremediation the combination of nanotechnology with phytoremediation, has proven to be very successful at enhancing plants uptake and degradation of pollutants. This is because the surface area of the nanoparticles is large, and they have many reactive sites [185]. Another benefit of this approach is that the nanoparticles can improve the properties of the soil and improve the development of plants and remove pollutants [186]. Biochar as a new product of the future, in which nanoparticles (NPs@BC) are attached, is extremely efficient in sequestering any heavy metals or organic pollutant contamination, and has also been successful in breaking soil aggregation for improved soil structure and productivity [187]. Furthermore, new nanocomposites have been developed which can remove both organic and inorganic contaminants simultaneously. In complicated situations, this guarantees more stable pollutant removal [188]. Biochar containing nano-particles (NPs@BC) has proven to be very effective in decontaminating soils and in reducing heavy metals and organic contaminants, thus exciting applications in agriculture. The enhanced mechanical strength, tumor catalyzing ability and high surface area of NPs@BC enable them to robustly eliminate the contaminations [189]. Biochar treated with nanoparticles has demonstrated outstanding efficiency in the adsorption and reactivity in removing organic pollutants and heavy metals thereby, helping to overcome the limitations of the use of ordinary biochar [190]. To harvest heavy metals through precipitation and complexation processes, such as, or foster microbial growth and plant stress tolerance, for example, one can use nanomaterials, e.g. nanosilica in biochar or add iron oxide nanoparticles to biochar [191]. In the case of rapid removal of organic contaminants, various nano-bioremediation techniques were able to remove contaminants rapidly, including magnetite and nano ZVI nanoparticles [192]. The use of PEI copper nanoparticles and TiO2 has also been demonstrated to be capable of greatly reducing the half-life of recalcitrant compounds such as phenanthrene and atrazine [193]. When combined with each other with biochar, graphene and oxide-incorporated functionalised nanoparticles exhibit better affinity with the pollutant, faster adsorption kinetic and selectivity [194].

Furthermore, the characteristics of microbe populations in the soil also change after adding the nanoparticles to the biochar structure. This involves the redesign of the network, introduction of metal-resistant species, induction of enzymes affecting oxidative damage in cells and modification of control genes of the plant hormones [191]. Sol-gel and in situ precipitation are techniques used to improve adsorption efficiency, efficiency and reusability, which result in uniform particle size and distribution. Moreover, associated studies demonstrates the ability of nano biochar generated from ball-milled wheat straw, bone and corn stalks to improve soil fertility and takes up triple the heavy metal ions as compared to the conventional biochar [196]. In addition, biochar can be better magnetized by introduction of metal or metal oxide nanoparticles, particularly the ones based on iron, which facilitates removal of the used biochar from the polluted environment [197].

9. Challenges and future perspectives

In spite of the momentum registered in the nanoparticle research in soil redressing, there are still several problems to overcome to make the nanoparticles marketable and useable in this context for extensive applications [198]. A key challenge is that the production and use of nanomaterials are unaffordable and not scalable. One way to solve this issue is to find alternative synthesis methods that are more environmentally friendly and cost-effective, including green synthesis [199]. Another problem is there is a lack of studies carried out in the field with an assessment of long-term environmental stability and performance of the nanomaterials in real soil environment [200]. The majority of the studies have taken place in laboratory controlled environments and further research is required to adopt the results into a practical application scenario [201]. Long term monitoring and risk assessment need to be performed to ensure the safety and effectiveness of soils treated with nanoparticles [202]. Future research needs to prioritise the development of novel materials with improved selectivity, stability and specificity towards their new target contaminants [203]. Specific ligands or biomolecules can be attached to the nanomaterials to enhance their adsorption capacity and selectivity towards specific contaminants [204]. Remediation may be more effective using a multifunctional approach by developing multifunctional nanomaterials with adsorption, reduction and degradation properties [205]. Improved cleaning and real-time monitoring are both made possible by combining nanomaterials with state-of-the-art technology, such as sensors and remote monitoring systems [206]. Adding nanosensors to the soil to identify and measure pollutants is critical for site characterization purpose and investigation strategies [207]. Potential risk of nanomaterials to soil can be effectively monitored by remote monitoring technologies [208].

10. CONCLUSION

Nanotechnology has proven to be an effective and beneficial approach to counteract soil pollution, as it is becoming a serious issue. Because of their unique physicochemical properties, nanomaterials can successfully remove, convert and stabilize a variety of pollutants. These features include a large surface area, sensitivity and the capacity to modify the working mechanisms of the surface. We will discuss the potential of nanomaterials to improve the biological remediation process and the soil physicochemical properties through photocatalysis, adsorption, catalytic degradation, redox reactions and redox reactions in this study.

By combining traditional remediation techniques, nanotechnology with biological and chemical remediation, enhances effectiveness and durability of cleaning operation effort. Additionally, novel approaches to the synthesis of nanomaterials offer environmentally friendly alternatives to traditional scaling-up processes that are inexpensive and environmentally friendly, that could be long-term solutions. Environmental toxicity, long-term stability, scalability, and cost-effectiveness are some of the difficulties that still need to be addressed, despite these encouraging improvements.

They should be evaluated carefully in the field to estimate their efficiency in practical use and novel nanomaterials with higher selectivity and stability should be developed that could improve their functionality in a environmentally friendly way. With the aim to ensure that the app is safe to use, a detailed risk assessment and certain rules are needed. Nano technologies are full of promise for a more natural and sustainable way to remediate soils in the future.

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Authors Contribution S.T conducted the literature survey, conceptualized the review, and prepared the original manuscript under the guidance of C.S.R. S.T. supervised the study, provided critical revisions, and improved the manuscript. R.M and K.P contributed suggestions for improving the manuscript. S.N. provided conceptual inputs. V.P.R. contributed ideas for figures and graphical content. All authors reviewed and approved the final manuscript.

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DECLARATIONS

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