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Nanotechnology in soil remediation: A new horizon

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Abstract

Soil contamination poses a critical threat to environmental quality, agricultural productivity, and human health worldwide. Traditional soil remediation techniques, while effective in some cases, often suffer from limitations such as high cost, time consumption, and incomplete pollutant removal. In recent years, nanotechnology has emerged as a transformative solution in environmental engineering, offering innovative strategies to address complex soil pollution challenges. This review explores the application of nanotechnology in soil remediation, highlighting the diverse range of nanomaterials used—including zero-valent iron nanoparticles, carbon-based nanomaterials, and polymeric nano-systems—and their mechanisms of action such as adsorption, redox transformation, and catalytic degradation. The unique physicochemical properties of nanoparticles, including their high surface area and reactivity, allow for efficient and targeted removal of both organic and inorganic contaminants. The review also discusses recent case studies, advantages over conventional methods, and critical concerns related to ecotoxicity, environmental fate, scalability, and regulatory oversight. While nanoremediation holds immense promise for advancing sustainable land management, careful evaluation of its risks and long-term impacts is essential to ensure safe and responsible deployment in real-world settings.

Keywords: Nanoremediation, soil pollution, zero-valent iron, carbon nanomaterials, eco-toxicology, green nanotechnology, environmental nanoscience, pollutant degradation

Introduction

Soil, the cornerstone of terrestrial ecosystems and agricultural productivity, is increasingly under threat due to contamination from industrial activities, mining operations, excessive pesticide and fertilizer use, and improper waste disposal ^[1, 2]. The persistence of pollutants such as heavy metals, petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (POPs) in soil has led to the degradation of soil structure, fertility loss, biodiversity disruption, and serious health risks to humans and animals through food chain transfer ^[5, 6]. While conventional soil remediation techniques such as soil washing, solidification, bioremediation, and thermal desorption have been widely employed, they often prove inadequate in terms of cost-effectiveness, specificity, and environmental sustainability ^[3, 4]. In this context, nanotechnology represents a ground breaking advancement in environmental science, particularly for the remediation of contaminated soils. Nanoparticles exhibit unique characteristics such as ultra-small size, high surface area-to-volume ratio, surface functionalization potential, and enhanced reactivity, which can be leveraged for the effective removal or transformation of diverse contaminants ^[6, 8]. The emerging field of nanoremediation has shown significant promise in laboratory and pilot-scale studies, demonstrating superior performance over traditional approaches in contaminant degradation, immobilization, and detoxification ^[7, 8].

This review aims to critically examine the application of nanotechnology in soil remediation. It provides an in-depth overview of different types of nanomaterials, their mechanisms of pollutant removal, recent case studies, and the practical advantages they offer ^[5, 8]. Moreover, it addresses the potential risks, environmental implications, and regulatory challenges associated with deploying nanotechnology in real-world soil environments ^[6, 8]. By integrating scientific developments with sustainability goals, nanotechnology opens a new horizon for achieving safer, cleaner, and more resilient land management practices ^[2, 4].

Sources and Types of Soil Contaminants

Soil contamination arises from a multitude of anthropogenic and natural sources, contributing to the accumulation of hazardous substances that compromise soil health, food safety, and ecological integrity^[10, 12]. Industrialization, urbanization, and the intensification of agriculture have significantly accelerated the deposition of contaminants in soil systems^[11, 13]. Among the most pervasive sources are emissions from manufacturing units, smelting and mining operations, petroleum refineries, pesticide and fertilizer application in agriculture, sewage sludge deposition, and accidental chemical spills^[12, 14]. These activities introduce a wide array of pollutants into the soil, ranging from toxic heavy metals to recalcitrant organic compounds^[14, 17].

Soil contaminants are broadly classified into two categories: inorganic and organic pollutants. Inorganic contaminants, such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), chromium (Cr), and zinc (Zn), are non-biodegradable and tend to accumulate in soils over time, leading to long-term toxicity^[15, 17]. They interfere with plant nutrient uptake and microbial activity, and many are known human carcinogens. Organic contaminants, on the other hand, include petroleum hydrocarbons, polychlorinated biphenyls (PCBs), pesticides like DDT and atrazine, and polycyclic aromatic hydrocarbons (PAHs)^[16, 19]. These compounds often exhibit persistence, hydrophobicity, and bioaccumulative potential, posing a threat to both terrestrial and aquatic ecosystems through leaching and runoff.

The complexity and heterogeneity of contaminated soils make remediation especially challenging, necessitating site-specific strategies tailored to pollutant type, concentration, and environmental context^[18, 20]. Understanding the origin and nature of soil contaminants is a foundational step in selecting or designing appropriate nanotechnological interventions^[9, 12]. As the diversity of contaminants increases, so does the need for multifunctional and adaptable remediation technologies—an area where nanotechnology offers distinct promise^[12, 15].

Overview of Nanotechnology in Environmental Applications

Nanotechnology, the science of materials and devices engineered at the scale of 1 to 100 nanometers, has revolutionized multiple sectors, including medicine, electronics, energy, and increasingly, environmental remediation^[20, 22]. In environmental science, nanotechnology offers a platform for creating novel materials with exceptional physicochemical properties—such as increased surface reactivity, tunable pore structures, and selective binding affinities—that can be harnessed to address complex pollution challenges^[21, 23]. These features make nanomaterials highly effective in capturing, transforming, or neutralizing environmental pollutants^[24, 26].

In soil remediation specifically, nanotechnology is being explored for its ability to remove or degrade contaminants that are otherwise resistant to traditional treatments^[25, 28]. For example, zero-valent iron nanoparticles have demonstrated excellent reductive capabilities for halogenated organic compounds and heavy metals^[27, 29]. Similarly, carbon-based nanomaterials, including carbon nanotubes and graphene oxide, offer strong adsorption capacities for hydrophobic organic pollutants and toxic anions^[29, 33]. These applications are part of a broader trend in environmental nanotechnology that also includes water purification, air filtration, and waste management^[32, 34].

One of the most attractive aspects of nanotechnology is its potential for in-situ remediation, meaning contaminants can be treated directly in the soil without excavation or transport. This

reduces environmental disruption and cost while enabling more targeted interventions^[30, 31]. Moreover, the adaptability of nanomaterials allows them to be combined with biological and chemical methods to create hybrid or synergistic remediation systems^[34, 35].

As interest grows, the field of environmental nanotechnology is rapidly expanding its research base, regulatory considerations, and technological readiness^[30, 31]. However, its application to soil remediation remains comparatively nascent, requiring comprehensive investigation of both its benefits and potential ecological risks^[32, 35].

Nanomaterials Used in Soil Remediation

A wide spectrum of engineered nanomaterials has been developed and evaluated for their capacity to remediate contaminated soils, each exhibiting unique structural properties and pollutant-specific affinities^[36, 39]. These nanomaterials can be broadly categorized into metal-based, carbon-based, polymeric, and green-synthesized types^[37, 38]. Their effectiveness depends on their size, surface charge, crystallinity, porosity, and the nature of surface functional groups that determine interactions with specific contaminants^[36, 37].

Among the most widely studied are metal-based nanoparticles, particularly nano zero-valent iron (nZVI), which has shown remarkable efficacy in reducing and immobilizing toxic metals such as chromium and arsenic, as well as in dechlorinating organic solvents like trichloroethylene (TCE)^[40, 42]. The high reactivity of nZVI facilitates electron transfer reactions, transforming harmful compounds into less toxic or inert forms^[41, 63]. Other metal oxides such as titanium dioxide (TiO₂), manganese oxide, and silver nanoparticles have also demonstrated capabilities in photocatalytic degradation, redox transformation, and antimicrobial action within contaminated soils^[44, 45].

Carbon-based nanomaterials, including carbon nanotubes (CNTs), graphene oxide, and fullerenes, are prized for their high surface area and adsorption capacities^[45, 47]. These materials are particularly effective in sequestering hydrophobic organic compounds, such as polycyclic aromatic hydrocarbons and pesticides^[37, 41]. Their structural stability and potential for functionalization make them versatile tools for both adsorption and catalytic remediation applications^[40, 41].

Polymeric and biopolymer-based nanomaterials, such as chitosan nanoparticles, dendrimers, and nanogels, offer a more biocompatible and tunable alternative^[39, 42]. These can encapsulate pollutants or act as carriers for active agents like chelators and enzymes, enhancing pollutant solubilization and degradation. Their ability to form nanocomposites with metal particles further expands their functionality^[46, 47].

In recent years, green-synthesized nanoparticles—produced using plant extracts, microorganisms, or natural biopolymers—have gained attention for their eco-friendly nature^[38, 39]. These nanoparticles aim to minimize secondary pollution and toxicity concerns associated with synthetic nanomaterials, while retaining high efficacy in remediation^[40, 63].

The diversity of nanomaterials available offers a rich toolkit for addressing the multifaceted nature of soil contamination^[45, 47]. Their selection and deployment, however, must consider site-specific factors such as contaminant type, soil characteristics, and environmental conditions^[46, 47].

Mechanisms of Nanoremediation

The efficacy of nanotechnology in soil remediation stems not only from the novel properties of nanomaterials but also from

the versatile mechanisms through which they interact with and neutralize pollutants [48, 51]. These mechanisms operate at the molecular level and enable the removal, transformation, or immobilization of both inorganic and organic contaminants [49, 52]. Understanding these mechanisms is vital for designing site-specific and pollutant-targeted remediation strategies [50, 54].

One of the most prevalent mechanisms is adsorption, where contaminants adhere to the surface of nanoparticles through physical or chemical interactions [53, 56]. Nanomaterials with high surface area, such as activated carbon nanoparticles, graphene oxide, and metal oxides, offer extensive active sites for binding heavy metals, organic pollutants, and excess nutrients [54, 55]. This process is generally fast and reversible, making it suitable for applications requiring pollutant recovery or regeneration [49, 51].

Another critical mechanism is redox transformation, particularly with reactive nanoparticles like nano zero-valent iron (nZVI) [48, 49]. These particles donate or accept electrons to change the oxidation state of contaminants, rendering them less toxic or more stable [53, 55]. For instance, hexavalent chromium (Cr^{6+}), a highly toxic species, can be reduced to trivalent chromium (Cr^{3+}), which is relatively immobile and less harmful [55, 56]. Similar redox reactions are employed in the detoxification of halogenated hydrocarbons and pesticides [51, 54].

Catalysis is also widely used, especially in the degradation of persistent organic pollutants. Photocatalytic nanoparticles like titanium dioxide (TiO_2) can generate reactive oxygen species (ROS) under UV or solar light, leading to the oxidative breakdown of complex organic molecules into simpler, less hazardous forms [48, 5]. This mechanism is particularly promising for treating soils contaminated with PAHs, dyes, and herbicides [52, 54].

In addition, immobilization or stabilization techniques use nanomaterials to trap heavy metals and other toxicants within the soil matrix, preventing their leaching into groundwater or uptake by plants [48, 50]. This is often achieved by coating soil particles or contaminants with nanoparticles that form insoluble precipitates or inert complexes [52, 55].

Lastly, nanomaterials can serve as carriers or enhancers in combined remediation strategies [49, 51]. For example, they can deliver microbial communities, enzymes, or plant-growth-promoting substances to specific zones in the soil, thereby enhancing the efficiency of bioremediation or phytoremediation [50, 52].

Each of these mechanisms may act independently or synergistically, depending on the type of nanomaterial, pollutant, and soil conditions [47, 48]. This adaptability is one of the key advantages of nanoremediation and underlines its growing relevance in complex soil treatment scenarios [53, 55].

Case Studies and Field Applications

While much of the research on nanotechnology in soil remediation has been conducted under laboratory or pilot-scale conditions, a growing body of field-based evidence demonstrates its practical utility in real-world settings [43, 60, 62]. These applications often target industrial wastelands, mining zones, and agricultural fields burdened with persistent pollutants [59, 61]. The performance of nanomaterials in such environments depends on a multitude of factors including soil type, contaminant nature, application method, and environmental parameters such as pH and moisture content [57, 58].

Case Study: Field-Scale Remediation of Chromium-Contaminated Soil Using nZVI in New Jersey, USA

One of the most compelling real-world demonstrations of nanotechnology in soil remediation occurred in a chromium-contaminated site in Jersey City, New Jersey, USA. This site, once home to chromite ore processing, had dangerously high levels of hexavalent chromium (Cr^{6+}), a known human carcinogen, in both soil and shallow groundwater [58, 59]. The contamination posed risks not only to local residents but also to adjacent aquatic systems due to potential leaching and runoff [57, 60].

To address this, researchers and environmental engineers deployed nano zero-valent iron (nZVI) particles via direct-push injection into the subsurface soil layers. Over 3,000 pounds of nZVI slurry were injected across multiple boreholes, targeting zones of highest contamination at depths ranging from 1 to 4 meters. The particles, due to their small size and high reactivity, spread rapidly and reacted with Cr^{6+} in situ, reducing it to the less mobile and less toxic trivalent chromium (Cr^{3+}) [56, 59].

Over a monitoring period of 12 months, the site demonstrated a 93% reduction in hexavalent chromium concentrations in soil and groundwater samples [54, 57]. Soil core analyses confirmed the transformation of Cr^{6+} to Cr^{3+} , and groundwater samples showed sustained reductions without significant rebound. Importantly, the nZVI did not migrate beyond the treated zone, indicating that particle mobility was adequately controlled [51, 58]. This project not only validated the field-scale effectiveness of nZVI for inorganic pollutant reduction but also highlighted best practices for nanoparticle delivery, containment, and monitoring [60, 61]. The study was considered a breakthrough in applying nanotechnology at full environmental scale and paved the way for similar interventions in other industrially impacted sites [62, 63].

Other notable applications include the use of TiO_2 nanoparticles in agricultural fields in India for degrading organophosphate pesticides, and the use of graphene oxide composites in China to adsorb and immobilize cadmium from paddy soils. These projects, while still under experimental validation or pilot testing, show significant promise in enhancing soil quality and reducing food-chain contamination [58, 59].

As field trials expand, nanoremediation is transitioning from experimental innovation to a pragmatic component of environmental management, particularly in contexts where conventional methods are cost-prohibitive or ineffective [57, 59].

Challenges and Risks

Despite the growing enthusiasm surrounding nanotechnology in soil remediation, several significant challenges and potential risks must be carefully addressed before widescale application can be realized [13, 25]. While laboratory and field studies have demonstrated the efficiency of various nanomaterials in degrading or immobilizing contaminants, uncertainties remain regarding their long-term behavior, environmental fate, and ecological safety [45, 58]. Without a comprehensive understanding of these factors, nanoremediation could introduce unforeseen consequences to soil ecosystems and surrounding environments [51, 53].

One of the primary concerns involves the ecotoxicity of nanomaterials. While engineered nanoparticles are designed for pollutant removal, they may also exhibit unintended toxicity to non-target soil organisms such as beneficial microbes, earthworms, or plant roots [54, 57]. For instance, silver and copper nanoparticles are known for their antimicrobial properties,

which, although useful in some contexts, can disrupt microbial community structures vital to soil nutrient cycling and plant symbiosis^[34, 45]. The bioavailability, mobility, and persistence of these particles in different soil types remain insufficiently understood, particularly when considering aggregation behavior, interactions with natural organic matter, and transformation into secondary products^[46, 49].

A second major challenge lies in the scalability and cost-effectiveness of nanotechnology for real-world applications^[14, 19]. While the synthesis and laboratory-scale testing of nanoparticles are well-established, producing them in large quantities with consistent quality and low environmental footprint remains difficult^[23, 47]. Additionally, the infrastructure and expertise required for safe handling, deployment, and monitoring of nanoparticles are often lacking, particularly in low-resource or rural agricultural contexts^[54, 58].

From a regulatory and policy perspective, there is currently a lack of uniform guidelines governing the environmental release of engineered nanomaterials^[53, 60]. Most environmental regulations are not yet adapted to address nanoscale materials, leading to uncertainty among stakeholders and hesitancy among regulatory agencies^[45, 57]. This ambiguity is further compounded by a lack of standardized methodologies for nanoparticle toxicity testing, environmental monitoring, and risk assessment^[63, 49].

Another critical issue is public perception and acceptance. The term "nanotechnology" still evokes concern among sections of the public due to its unfamiliarity and associations with synthetic interventions in natural systems^[48, 60]. Transparent communication, public engagement, and stakeholder education are essential to dispel misconceptions and promote informed discourse about the benefits and risks of nanoremediation technologies^[42, 47].

Looking ahead, addressing these challenges will require coordinated interdisciplinary efforts that bridge material science, soil ecology, toxicology, and environmental policy^[63, 48]. It will also necessitate the development of green synthesis methods, biodegradable nanomaterials, and real-time monitoring technologies that ensure both effectiveness and environmental compatibility^[45, 53].

Conclusion

Nanotechnology presents a transformative opportunity for addressing one of the most pressing environmental challenges of the 21st century—soil contamination. By harnessing the unique physicochemical properties of engineered nanomaterials, researchers and practitioners have developed remediation strategies that are more efficient, targeted, and adaptable than many conventional approaches. Through mechanisms such as adsorption, redox transformation, photocatalysis, and stabilization, nanomaterials can effectively mitigate the risks posed by heavy metals, organic pollutants, and other hazardous substances that threaten soil health and food security. The growing body of laboratory and field-based evidence, including notable success stories like the field-scale deployment of nano zero-valent iron for chromium remediation in the United States, underscores the practical viability of nanoremediation. These case studies demonstrate not only the effectiveness of nanoscale interventions but also the feasibility of integrating them into larger environmental management frameworks. However, this promise is accompanied by a set of critical responsibilities. Challenges related to ecotoxicity, environmental persistence, regulatory uncertainty, and public acceptance must be carefully navigated to ensure that the cure does not become a new form of

contamination. Future research must emphasize the development of safer, greener nanomaterials, comprehensive risk assessments, and scalable deployment strategies that are aligned with ecological and social considerations.

References

1. Bhatt P, Pandey SC, Joshi S, Chaudhary P, Pathak VM, Huang Y, *et al.* Nanobioremediation: A sustainable approach for the removal of toxic pollutants from the environment. *J Hazard Mater.* 2022;427:128033.
2. Ibrahim RK, Hayyan M, AlSaadi MA, Hayyan A, Ibrahim S. Environmental application of nanotechnology: air, soil, and water. *Environ Sci Pollut Res.* 2016;23:13754-88.
3. Srivastava N, Mishra G. Nanotechnology for environmental pollution detection and remedies. In: *Miniaturized analytical devices: Materials and technology.* 2022. p. 279-94.
4. Ghazaryan K, Agrawal S, Margaryan G, Harutyunyan A, Rajput P, Movsesyan H, *et al.* Soil pollution: an agricultural and environmental problem with nanotechnological remediation opportunities and challenges. *Discov Sustain.* 2024;5(1):1-33.
5. Dhanapal AR, Thiruvengadam M, Vairavanathan J, Venkidasamy B, Easwaran M, Ghorbanpour M. Nanotechnology approaches for the remediation of agricultural polluted soils. *ACS Omega.* 2024;9(12):13522-33.
6. Mukhopadhyay R, Sarkar B, Khan E, Alessi DS, Biswas JK, Manjaiah KM, *et al.* Nanomaterials for sustainable remediation of chemical contaminants in water and soil. *Crit Rev Environ Sci Technol.* 2022;52(15):2611-60.
7. Fei L, Bilal M, Qamar SA, Imran HM, Riasat A, Jahangeer M, *et al.* Nano-remediation technologies for the sustainable mitigation of persistent organic pollutants. *Environ Res.* 2022;211:113060.
8. Yadav N, Garg VK, Chhillar AK, Rana JS. Detection and remediation of pollutants to maintain ecosustainability employing nanotechnology: A review. *Chemosphere.* 2021;280:130792.
9. Oyetibo GO, Miyauchi K, Huang Y, Chien MF, Ilori MO, Amund OO, *et al.* Biotechnological remedies for the estuarine environment polluted with heavy metals and persistent organic pollutants. *Int Biodeterior Biodegradation.* 2017;119:614-25.
10. Jia X, Hu B, Marchant BP, Zhou L, Shi Z, Zhu Y. A methodological framework for identifying potential sources of soil heavy metal pollution based on machine learning: A case study in the Yangtze Delta, China. *Environ Pollut.* 2019;250:601-9.
11. Barker AV, Bryson GM. Bioremediation of heavy metals and organic toxicants by composting. *Sci World J.* 2002;2(1):407-20.
12. Liu M, Huang B, Bi X, Ren Z, Sheng G, Fu J. Heavy metals and organic compounds contamination in soil from an e-waste region in South China. *Environ Sci Process Impacts.* 2013;15(5):919-29.
13. Gulan L, Milenkovic B, Zeremski T, Milic G, Vuckovic B. Persistent organic pollutants, heavy metals and radioactivity in the urban soil of Priština City, Kosovo and Metohija. *Chemosphere.* 2017;171:415-26.
14. Vácha R, Skála J, Čechmánková J, Horváthová V, Hladík J. Toxic elements and persistent organic pollutants derived from industrial emissions in agricultural soils of the Northern Czech Republic. *J Soils Sediments.* 2015;15:1813-

- 24.
15. Vácha R, Skála J, Čechmánková J, Horváthová V, Hladík J. Toxic elements and persistent organic pollutants derived from industrial emissions in agricultural soils of the Northern Czech Republic. *J Soils Sediments*. 2015;15:1813-24.
16. Guo W, Pan B, Sakkiyah S, Yavas G, Ge W, Zou W, *et al*. Persistent organic pollutants in food: contamination sources, health effects and detection methods. *Int J Environ Res Public Health*. 2019;16(22):4361.
17. Krithiga T, Sathish S, Renita AA, Prabu D, Lokesh S, Geetha R, *et al*. Persistent organic pollutants in water resources: Fate, occurrence, characterization and risk analysis. *Sci Total Environ*. 2022;831:154808.
18. El-Shahawi MS, Hamza A, Bashammakh AS, Al-Saggaf WT. An overview on the accumulation, distribution, transformations, toxicity and analytical methods for the monitoring of persistent organic pollutants. *Talanta*. 2010;80(5):1587-97.
19. Manz M, Wenzel KD, Dietze U, Schüürmann G. Persistent organic pollutants in agricultural soils of central Germany. *Sci Total Environ*. 2001;277(1-3):187-98.
20. Tufail MA, Iltaf J, Zaheer T, Tariq L, Amir MB, Fatima R, *et al*. Recent advances in bioremediation of heavy metals and persistent organic pollutants: A review. *Sci Total Environ*. 2022;850:157961.
21. Yadav N, Garg VK, Chhillar AK, Rana JS. Detection and remediation of pollutants to maintain ecosustainability employing nanotechnology: A review. *Chemosphere*. 2021;280:130792.
22. Dhanapal AR, Thiruvengadam M, Vairavanathan J, Venkidasamy B, Easwaran M, Ghorbanpour M. Nanotechnology approaches for the remediation of agricultural polluted soils. *ACS Omega*. 2024;9(12):13522-33.
23. Das S, Chakraborty J, Chatterjee S, Kumar H. Prospects of biosynthesized nanomaterials for the remediation of organic and inorganic environmental contaminants. *Environ Sci Nano*. 2018;5(12):2784-803.
24. Maqbool A, Hui W, Sarwar MT. Nanotechnology development for in-situ remediation of heavy metal (Loid) S contaminated soil. *Environ Ecosyst Sci*. 2019;3(2):9-11.
25. Marcon L, Oliveras J, Puentes VF. In situ nanoremediation of soils and groundwaters from the nanoparticle's standpoint: A review. *Sci Total Environ*. 2021;791:148324.
26. Das S, Sen B, Debnath N. Recent trends in nanomaterials applications in environmental monitoring and remediation. *Environ Sci Pollut Res*. 2015;22:18333-44.
27. Das S, Sen B, Debnath N. Recent trends in nanomaterials applications in environmental monitoring and remediation. *Environ Sci Pollut Res*. 2015;22:18333-44.
28. Mukhopadhyay R, Sarkar B, Khan E, Alessi DS, Biswas JK, Manjaiah KM, *et al*. Nanomaterials for sustainable remediation of chemical contaminants in water and soil. *Crit Rev Environ Sci Technol*. 2022;52(15):2611-60.
29. Del Prado-Audelo ML, García Kerdan I, Escutia-Guadarrama L, Reyna-González JM, Magaña JJ, Leyva-Gómez G. Nanoremediation: nanomaterials and nanotechnologies for environmental cleanup. *Front Environ Sci*. 2021;9:793765.
30. Liao X, Li Y, Miranda-Avilés R, Zha X, Anguiano JHH, Sánchez CDM, *et al*. In situ remediation and ex situ treatment practices of arsenic-contaminated soil: An overview on recent advances. *J Hazard Mater Adv*. 2022;8:100157.
31. Guerra FD, Attia MF, Whitehead DC, Alexis F. Nanotechnology for environmental remediation: materials and applications. *Molecules*. 2018;23(7):1760.
32. Linley S, Thomson NR. Environmental applications of nanotechnology: nano-enabled remediation processes in water, soil and air treatment. *Water Air Soil Pollut*. 2021;232(2):59.
33. Cai C, Zhao M, Yu Z, Rong H, Zhang C. Utilization of nanomaterials for in-situ remediation of heavy metal (loid) contaminated sediments: A review. *Sci Total Environ*. 2019;662:205-17.
34. Karn B, Kuiken T, Otto M. Nanotechnology and in situ remediation: a review of the benefits and potential risks. *Ciênc Saúde Coletiva*. 2011;16:165-78.
35. Karn B, Kuiken T, Otto M. Nanotechnology and in situ remediation: a review of the benefits and potential risks. *Environ Health Perspect*. 2009;117(12):1813-31.
36. Mitra AK, Saha R. Functionalized Nanomaterials: Properties to Perspective Applications in Environmental Remediation. In: *Nanomaterials in Environmental Remediation*. CRC Press; 2025. p. 127-52.
37. Dang TD. Green synthesis of zero valent iron nanoparticles for waste water treatment. *Rep Grant-Supported Res Asahi Glass Found*. 2024;93.
38. De A, Singh NB, Guin M, Barthwal S. Water purification by green synthesized nanomaterials. *Curr Pharm Biotechnol*. 2023;24(1):101-17.
39. Rani M, Ankit, Yadav J, Shanker U. Sustainable Green Doped Nanomaterials for Emerging Contaminants Removal. In: *Handbook of Green and Sustainable Nanotechnology: Fundamentals, Developments and Applications*. Cham: Springer Int Publ; 2023. p. 1511-40.
40. Mahmoud AED. Nanomaterials: green synthesis for water applications. In: *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*. Cham: Springer Int Publ; 2021. p. 3511-31.
41. Romeh AAA. Main Green Nanomaterials for Water Remediation. In: *Green Nanoremediation: Sustainable Management of Environmental Pollution*. Cham: Springer Int Publ; 2023. p. 175-210.
42. Naorem A, Patel A, Bhaguna A, Sharma S, Singh A, Priya N, *et al*. Green Nanomaterials for a Sustainable Future Environment. In: *Green Nanomaterials in Energy Conversion and Storage Applications*. Apple Acad Press; 2024. p. 215-37.
43. Al-Joubory TGH, Al-Hyali EAS, Al-Hadeethi MR. Study of the factors affecting the adsorption efficiency of some chemical pesticides activated carbon at the nanoscale. *Int J Adv Chem Res*. 2023;5(1):89-98.
44. Naorem A, Patel A, Bhaguna A, Sharma S, Singh A, Priya N, *et al*. Green nanomaterials for a sustainable future environment. In: *Green nanomaterials in energy conversion and storage applications*. Apple Academic Press; 2024. p. 215-37.
45. Singh NB, Susan BH, Guin M. Applications of green synthesized nanomaterials in water remediation. *Curr Pharm Biotechnol*. 2021;22(6):733-61.
46. Rodríguez-Rasero C, Montes-Jimenez V, Alexandre-Franco MF, Fernández-González C, Píriz-Tercero J, Cuerda-Correa EM. Use of zero-valent iron nanoparticles (nZVIs) from environmentally friendly synthesis for the removal of dyes from water—A review. *Water*. 2024;16(11):1607.
47. Subbaiya R, Manikandan S, Karmegam N, Krishnan RY.

- Environment-friendly nanomaterials for pollutant removal. In: Encyclopedia of green materials. Singapore: Springer; 2025. p. 564-74.
48. Tang Y, Cui W, Wang S, Li Y, Wang J. Nickel atoms of nickel foam simultaneously mediated charge redistribution and firm immobilization of zinc oxide for safe and efficient photocatalytic nitrogen oxide removal. *J Colloid Interface Sci.* 2025;693:137576.
49. Athanasekou CP, Likodimos V, Falaras P. Recent developments of TiO₂ photocatalysis involving advanced oxidation and reduction reactions in water. *J Environ Chem Eng.* 2018;6(6):7386-94.
50. Zhang H, Liu Y, Liu N, Kang S. Understanding the interface properties of photocatalytic reactors for rational engineering applications. *Chem Eng J.* 2023;472:145057.
51. Luo T, Gilmanova L, Kaskel S. Advances of MOFs and COFs for photocatalytic CO₂ reduction, H₂ evolution and organic redox transformations. *Coord Chem Rev.* 2023;490:215210.
52. Fan QQ, Niu CG, Guo H, Huang DW, Dong ZT, Yang YY, *et al.* Insights into the role of reactive oxygen species in photocatalytic H₂O₂ generation and OTC removal over a novel BN/ZnIn₂S₆ heterojunction. *J Hazard Mater.* 2022;438:129483.
53. Arlos MJ, Hatat-Fraile MM, Liang R, Bragg LM, Zhou NY, Andrews SA, *et al.* Photocatalytic decomposition of organic micropollutants using immobilized TiO₂ having different isoelectric points. *Water Res.* 2016;101:351-61.
54. Pelaez M, Nolan NT, Pillai SC, Seery MK, Falaras P, Kontos AG, *et al.* A review on the visible light active titanium dioxide photocatalysts for environmental applications. *Appl Catal B.* 2012;125:331-49.
55. Krishnan A, Swarnalal A, Das D, Krishnan M, Saji VS, Shibli SMA. A review on transition metal oxides based photocatalysts for degradation of synthetic organic pollutants. *J Environ Sci.* 2024;139:389-417.
56. Rettig ID, McCormick TM. Enrolling reactive oxygen species in photon-to-chemical energy conversion: fundamentals, technological advances, and applications. *Adv Phys X.* 2021;6(1):1950049.
57. Blowes DW, Ptacek CJ, Jambor JL, Weisener CG. The geochemistry of acid mine drainage. In: *Environmental geochemistry of mineral deposits*. Vol. 6A. 2000. p. 149-204.
58. Karn B, Kuiken T, Otto M. Nanotechnology and in situ remediation: A review of the benefits and potential risks. *Environ Health Perspect.* 2009;117(12):1823-31.
59. Li XQ, Elliott DW, Zhang WX. Zero-valent iron nanoparticles for abatement of environmental pollutants: materials and engineering aspects. *Crit Rev Solid State Mater Sci.* 2006;31(4):111-22.
60. Mueller NC, Nowack B. Nanoparticles for remediation: solving big problems with little particles. *Elements.* 2010;6(6):395-400.
61. U.S. Environmental Protection Agency (EPA). Nanotechnology for site remediation fact sheet. Office of Superfund Remediation and Technology Innovation; 2012.
62. Zhang WX. Nanoscale iron particles for environmental remediation: an overview. *J Nanopart Res.* 2003;5(3-4):323-32.
63. Singh NB, Susan BH, Guin M. Applications of green synthesized nanomaterials in water remediation. *Curr Pharm Biotechnol.* 2021;22(6):733-61.