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Chapter 7

Application of Nanotechnology in Soil Remediation and Water Management

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Abstract: Particularly in the areas of water management and soil remediation, nanotechnology has shown great promise as a solution for tackling environmental issues. Engineered nanoparticles (ENPs), such as metal oxides, carbon nanotubes and zero-valent iron, offer efficient and cost-effective alternatives for eliminating heavy metals, organic contaminants and pathogens from contaminated soil and water systems. In soil remediation, nanoparticles increase the breakdown of contaminants, facilitate nutrient availability and improve soil structure, ultimately restoring fertility. In water management, nanoparticles are utilized for enhanced filtration, adsorption and disinfection procedures, ensuring the removal of hazardous pollutants and increasing water quality. The high surface area, reactivity and tuneable features of nanoparticles make them excellent for targeted and sustained environmental interventions. However, worries regarding the possible environmental and human health dangers of nanoparticle applications demand greater research on their long-term implications. This study discusses the many applications of nanotechnology in soil remediation and water management, highlighting the possible benefits and resolving the accompanying problems.

Keywords: Nanotechnology, soil remediation, water management, engineered nanoparticles, heavy metals.

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1 Introduction

Nanotechnology is an interdisciplinary discipline of science and engineering that involves the exact manipulation, creation and application of materials, structures and devices at the nanoscale, often within the range of 1 to 100 nanometres. Compared to its macroscopic counterparts, matter at this size possesses distinct quantum, mechanical, optical, and electromagnetic properties. Nanotechnology makes it possible to create new materials, nanoelectromechanical systems (NEMS), tailored medication delivery systems, and sophisticated electrical components by utilizing concepts from physics, chemistry, biology, and materials science. Nano technology is spreading rapidly across the world as a more powerful technology. Nanotechnology controls the matter at its atomic level, thus the properties like strength, hardness, durability, etc. of matter are considerably affected under the scale of nanometers (10^{-9}m). Its small size and high surface to volume ratio gives very special and unique properties to it, which can be used in our practical problems. The essential needs of today's industry are to design and develop a higher efficient system with minimum losses. The use of nano science is able to fulfill this current requirement with maintaining high accuracy. Nano technology is broadly used in various fields, mainly in wear and corrosive environments such as nano composite materials, nanostructured coatings (in hydro turbine blades, coal fired boiler etc.), cutting tools, nano fluids (to increase heat transfer rates of fluid), building materials and in automotive industries to enhance the effectiveness of that particular system (Sharma *et al.*, 2018). This transformative technology underpins innovations in diverse sectors, including medicine, energy, computing and environmental remediation, by exploiting atomic and molecular-level interactions to achieve unprecedented precision and efficiency in material performance and functionality. Nanotechnology in India is swiftly emerging as a catalyst for transformative advancements across diverse sectors, ranging from medicine to textiles. However, challenges around regulation, environment and ethical aspects need addressing. India can reap nanotechnology's benefits across sectors to achieve progress in science, economy and society aligned with the United Nations Sustainable Development Goals.

2 Types of Nanotechnology

There are several different types of nanotechnology, each with their own unique applications and characteristics. Some examples include:

2.1 Nanomaterials: The materials, having one dimension in the range of 1–100 nm, are known as nanomaterials (Sohail *et al.,* 2019). Nanomaterials differ from bulk materials in many features, including size, shape, surface area and reactivity and it is the main reason for their excellent performance in many applications (Kalambate *et al.,*2019; Paneru & Kumar, 2023). Nanomaterials have enabled new devices and products that demonstrated better efficiency than conventional bulk materials (Đorđević *et al.,* 2019; Thomas *et al.,* 2015). Nanomaterial-based products are now entering commercial markets (Fu *et al.*, 2011; Kumari *et al.*, 2010), including sensors, electronic products, paints, cosmetics, energy storage, conversion devices, biomedical imaging and so on. The area of nanotechnology has grown at an unprecedented pace in the last couple of decades and several new materials have been developed. Moreover, substantial advances have been reported in the synthesis of nanomaterials with better control on their size, shape and properties (Su *et al.*, 2010; Roca *et al.*, 2019 and Tian *et al.*, 2018). Nanomaterials are super tiny materials engineered at the nanoscale, giving them cool new properties compared to regular materials. Some examples are as Carbon nanotubes, nanoparticles and quantum dots. Carbon nanotubes are insanely strong and super conductive, making them Nanoparticles, on the other hand, are tiny particles made from metals, oxides, or polymers. They're used in everything from medical treatments to cosmetics and even environmental tech. Then, there are quantum dots-these tiny semiconductor particles power things like high-quality displays, solar cells and medical imaging.

2.2 Nanoelectronics: Nanoelectronics is all about using super small transistors and components at the nanoscale to make faster, more efficient devices. Think nanoscale transistors and memory devices that take tech to the next level. These tiny components allow gadgets to be smaller, use less energy and handle way more data than traditional electronics. It's the future of faster, smarter tech!

2.3 Nano-optics: This field manipulates light at the nanoscale to create innovative optical devices like nano-antennas and nano-optical fibers, enhancing communication systems and medical imaging technologies.

2.4 Nanomedicine: Nanotechnology is applied in medicine through tiny particles for diagnosing and treating diseases, such as targeted drug delivery systems that reduce side effects and diagnostic nanoparticles for early disease detection and high-resolution imaging.

2.5. Nano-energy: In the energy sector, nanotechnology improves efficiency with devices like nano-solar cells, nano-batteries and nano-fuel cells, which are smaller and lighter while offering better performance than traditional options.

2.6. Nano-robotics: This area focuses on developing tiny robots and machines, such as molecular machines and nanorobots, capable of assembling, repairing, or performing medical tasks within the human body.

These examples showcase the diverse applications of nanotechnology, with ongoing research continuously pushing the boundaries of the field.

3 Roles of nanotechnology

3.1 Medical applications: Nanotechnology is transforming medicine with nanoparticles that deliver drugs directly to cancer cells, reducing chemotherapy side effects. They also create contrast agents for MRI and CT scans, enabling earlier disease detection with nano-biosensors for conditions like cancer and heart disease.

3.2 Materials science: By combining nanoparticles with polymers, nanocomposites produce materials that are stronger, lighter and more durable. Nanoparticles enhance coatings, making them more wear- and corrosion-resistant than traditional options.

3.3 Energy storage and production: Nanotechnology improves energy solutions, making solar cells more efficient and cost-effective, while nanoparticles in batteries boost energy density, extend lifetimes and allow for quicker charging.

3.4 Environmental applications: Nanoparticles play a role in environmental cleanup by removing heavy metals from water and soil and they create catalysts that convert pollutants into less harmful substances.

3.5 Electronics and computing: In electronics, nanoparticles enable smaller, faster and more energy-efficient transistors, as well as memory devices with higher storage capacities.

3.6 Cosmetics and personal care products: In cosmetics, nanoparticles enhance product effectiveness, allowing sunscreens to block UV rays more effectively and skincare products to penetrate the skin better.

4 Nanotechnology in Soil Remediation

4.1 Mechanisms of Nano-based Soil Remediation

Nanotechnology offers various methods to decontaminate polluted soils effectively. Some of the key mechanisms include:

4.1.1 Nanoparticle Adsorption: Engineered nanoparticles such as carbon-based nanomaterials and metal oxides (e.g., iron oxide, titanium dioxide) can adsorb heavy metals and organic pollutants, preventing their spread. Nanoparticles offer distinct advantages over traditional soil remediation methods, primarily because of their size and surface area (Sathish *et al.*, 2024). Various types of nanoparticles are effective in cleansing and detoxifying diverse pollutants, as discussed comprehensively herein. Ongoing research and interdisciplinary collaboration promise further research in this intriguing field. Although planetary reclamation remains challenging, nano-phytoremediation has emerged as a promising solution to address these environmental issues. Soil pollution and degradation pose urgent global environmental challenges that impact agricultural productivity, food security and human well-being (Gomiero, 2016).

4.1.2 Chemical Reduction: Zero-valent iron (ZVI) nanoparticles facilitate the reduction of toxic metal ions such as lead (Pb) and arsenic (As) into less harmful forms. Reduction reactions, facilitated by nZVI nanoparticles, exhibit significant potential for eliminating heavy metals and organic compounds from contaminated soil as well as addressing water and groundwater contamination (Galdames, 2020). The widespread application of nZVI particles in various fields is attributed to their nanoparticle size and large surface area, which enhance remediation efficiency by direct contact with contaminants. The injection of nZVI particles into contaminated soil demonstrates their strong reduction capacity and effective adsorption ability, transforming toxic contaminants such as chromium (VI) into less harmful compounds such as chromium (III) and the formation of new compounds such as ferrous chromite (Liang, 2022).

4.1.3 Catalytic Degradation: Photocatalytic nanoparticles like TiO_2 and ZnO degrade organic contaminants, including pesticides and petroleum hydrocarbons. Widely used nanotechnological applications in soil remediation for contaminant removal include carbon nanomaterials, iron (III) oxide (Fe_3O_4), titanium oxide (TiO_2), zinc oxide (ZnO), nZVI and nanocomposites (Asghar, 2024).

4.1.4 Bioremediation Enhancement: Nanomaterials can enhance microbial activity in bioremediation by delivering nutrients or enzymes to contaminated sites.

4.2 Types of Nanomaterials Used in Soil Remediation

4.2.1 Carbon-based Nanomaterials: Carbon nanotubes (CNTs), graphene oxide and biochar-based nanoparticles improve adsorption capacities for organic and inorganic pollutants.

4.2.2 Metal and Metal Oxide Nanoparticles: Iron, silver, zinc oxide and titanium dioxide nanoparticles are used for heavy metal immobilization and degradation of organic pollutants.

4.2.3 Polymeric Nanomaterials: Functionalized polymer-based nanomaterials assist in the controlled release of remediation agents for prolonged effectiveness. The presence of dangerous substances in the natural soil environment leads to soil contamination. Heavy metals are common soil pollutants that can occur naturally in soil but rarely at toxic levels. Mining, manufacturing, landfills, especially those that accept industrial wastes (such as paint residues, batteries, electrical wastes, etc.), and municipal or industrial sludge are the main sources of contaminated soil. Because they are non-biodegradable and remain in the contaminated environment after being introduced, heavy metals can be regarded as one of the more difficult soil pollutants. The only exceptions are mercury and selenium, which can be altered and volatilized by microorganisms. Although huge amounts of polluted soil can be treated either in situ (on-site) or ex situ (taken and treated off-site), the conventional methods of treating contaminated soil are very complex and expensive (Natural Resources Conservation Service 2000). Therefore, preventing heavy metal pollution or using the immobilization technique to stop heavy metals from spreading in soil are the best ways to safeguard the ecosystem (Ma *et al.,* 1993). A variety of amendment agents have been used to control the bioavailability of heavy metals and to prevent their diffusion in soil by causing different sorption processes, such as adsorption to mineral surfaces, formation of stable complexes with organic ligands, surface precipitation, and ion exchange (Kumpiene *et al.,* 2008). This is because the activity of heavy metals in soil is controlled by sorption–desorption reactions with other soil constituents (Singh *et al.,* 2001). Figure 1 illustrates the two categories of amendment agents that Robinson et al. (2019) claim exist. Immobilizing amendment agents reduce the mobility and bioavailability of heavy metals and lessen their transfer to the food chain by stopping their leaching to the groundwater (i.e., phyto-stabilization), while mobilizing agents increase the mobility and bioavailability of heavy metals and improve their removal through plant intake and soil washing (i.e., phytoextraction process). The phytoremediation approach is used to manage contaminated soils and includes both phytoextraction and phyto-stabilization processes (Bolan *et al.,* 2014).

Recently, there has been a lot of interest in using nanoscale particles to immobilize heavy metals in groundwater and soil. When using nanoparticles as amendment agents, An and Zhao (2012) discovered that two crucial conditions must be fulfilled: (a) the nanoparticles must be able to be delivered to the contaminated zones; and (b) the delivered nanoparticles must stay within the confined domain (i.e., under natural groundwater conditions) after the external injection pressure is removed. In this situation, the delivered nanoparticles will act as an immobile sink for absorbing soluble metals. However, nanoparticles lose their unique properties, like high specific surface area and soil deliverability, due to their quick propensity to aggregate into micro- to millimeter-scale aggregates. In order to overcome these issues, organic polymers like starch and carboxymethyl cellulose (CMC) are frequently affixed to the nanoparticles as stabilizers. This is done in order to increase the specific surface area and improve the physical stability and mobility in soil, as well as to prevent nanoparticle agglomeration through steric and/or electrostatic stabilization mechanisms (He & Zhao, 2007). According to Liang & Zhao (2014), starch-stabilized magnetite nanoparticles were found to be effective for in situ enhanced sorption and immobilization of arsenate As(V); the results showed that both the toxicity characteristic leaching procedure (TCLP) leachability of As(V) and water-leachable As(V) were significantly reduced.

5 Nanotechnology in Water Management

5.1 Nano-filtration and Water Purification:

Nanofiltration membrane (NF) is one of the most important activities employed in wastewater treatment field. It is a relatively recent development in membrane technology and it can be aqueous or non-aqueous. Characteristics of NF fall between UF and RO and functions by both pore-size flow (convective) and the solution-diffusion mechanisms. Membrane charges play an important role in membrane function and often NF membrane as have surface negative charges. NF technique is used in a variety of water and wastewater treatment (WWT) in different industrial applications. The main job of NF is the selective removal of ions and organic substances and it is used in some specified seawater desalination application. The main objective of this review is to illustrate the main applications of NF process in water reuse, WWT as tertiary treatment, water softening and desalination fields (Mona A. Abdel- Fatah, 2018). Phytoremediation is a successful, eco-friendly and reasonably priced type of bioremediation. This technique is increasingly being used to clean areas contaminated with toxic organic compounds and heavy metals. Additionally, radioactive pollutants can be eliminated from agricultural fields and groundwater using this technique. A cheap technique known as phytoremediation functions best when pollutants are found in the root zones of plants (Prakash *et al.*, 2023).

Nanotechnology significantly improves water purification and filtration through various advanced techniques. Nano-membranes with high selectivity efficiently remove heavy metals, bacteria, viruses, and organic pollutants, ensuring cleaner water sources. Photocatalysis, utilizing nanoparticles like titanium dioxide (TiO_2) and zinc oxide (ZnO), harnesses solar energy to break down contaminants, making water safe for consumption. Magnetic nanoparticles offer an innovative approach by enabling the separation of pollutants through the application of external magnetic fields. Additionally, nano-sensors, composed of advanced nanomaterials, detect waterborne pollutants at ultra-low concentrations, allowing real-time monitoring of water quality. These nanotechnology driven solutions contribute to more effective and sustainable water purification systems.

5.2 Desalination and Water Treatment

With the rising demand for freshwater, nanotechnology plays a crucial role in desalination and water treatment. Nanocomposite membranes enhance the efficiency of reverse osmosis by improving permeability and resistance to fouling, making desalination more effective. Additionally, nano-adsorbents, composed of functionalized nanomaterials, efficiently remove salts, heavy metals, and harmful chemicals from seawater and wastewater, providing cleaner water resources. Beyond desalination, nanotechnology offers significant advantages in environmental applications. Nanomaterials exhibit high surface area and reactivity, ensuring faster and more efficient remediation processes. These solutions are also cost-effective, requiring less material and energy compared to traditional methods. Furthermore, many nanomaterials are designed to be biodegradable, promoting sustainability while minimizing environmental impact. Functionalized nanoparticles enable targeted remediation by specifically binding to contaminants, reducing the risk of secondary pollution. These advancements make nanotechnology a promising tool for addressing global water and environmental challenges.

6 Challenges and Future Prospects

One of the most crucial factors influencing soil nutrient availability, microbial dynamics, general soil health, and plant growth and development is pH, which is said to be changed by NPs in soils (Rajput *et al.,* 2022). One of the main variables affecting soil nutrient availability, microbial dynamics, overall soil health, and plant growth and development is pH, which has been demonstrated to be altered by NPs in soils. Furthermore, it has been observed that NPs of Ag, Au, Ti, and Zn change the pH of the soil and negatively affect beneficial soil microorganisms and nematodes. The degree of NPs' negative impacts depends on the kind and concentration of NPs that are present in the soil, as well as the soil's enzymatic activity. Furthermore, a decrease in dehydrogenase activity is linked to an increased NP concentration, which increases the balance between soil fertility and nutrient levels (Khan *et al.,* 2021). Additionally, the uptake and assimilation of these nanoparticles by microorganisms profoundly affect the mycelium, impairing their regular cellular operations. Despite its numerous advantages, the implementation of nanotechnology in environmental remediation faces several challenges. Potential toxicity remains a key concern, as some nanoparticles may pose ecological and health risks due to their unknown long-term effects. Scalability is another hurdle, as large-scale applications require cost-effective and efficient production methods for nanomaterials. Additionally, regulatory uncertainty persists, with standardized guidelines for the safe use of nanotechnology in soil and water management still under development. Public acceptance also plays a crucial role, as concerns regarding safety and ethical implications may hinder widespread adoption. To overcome these challenges, future research should focus on developing eco-friendly nanomaterials, enhancing cost-effectiveness, and addressing regulatory concerns. Innovations in green nanotechnology, such as bio-based and biodegradable nanomaterials, offer promising solutions for sustainable environmental remediation.

Conclusions

Nanotechnology presents a groundbreaking approach to soil remediation and water management, offering innovative solutions to pollution and resource scarcity. With its ability to efficiently remove contaminants, enhance water purification and support sustainable agricultural practices, nanotechnology is set to revolutionize environmental science. However, addressing potential risks and regulatory challenges is crucial to ensure its safe and effective implementation. By integrating nanotechnology with traditional remediation strategies, we can pave the way for a cleaner and healthier environment. To improve the efficacy and security of nanomaterials, exhaustive investigation of their enduring ecological ramifications is imperative. Furthermore, it is imperative to investigate uncharted territories, including the advancement of innovative nanomaterials and the refinement of Nano-phytoremediation methodologies. This chapter provides a comprehensive overview of the role of nanotechnology in soil remediation and water management, highlighting both its transformative potential and associated challenges.

References

Abdel-Fatah, M. A. (2018). Nanofiltration systems and applications in wastewater treatment: Review article. Ain Shams Engineering Journal, 9(2), 307–322.

Asghar, N. (2024). Nanotechnology applications in soil remediation: Advances and challenges. Environmental Science Journal, 15(2), 112-125.

Bolan, N. S., Park, J. H., Robinson, B., Naidu, R., & Huh, K. Y. (2014). Phytostabilization: A green approach to contaminant containment. Advances in Agronomy, 126, 151-196. https://doi.org/10.1016/B978-0-12-800132-5.00004-4

Đorđević, L., Arcudi, F., & Cacioppo, M. (2019). Preparation, functionalization and characterization of engineered carbon nanodots. Nature Protocols, 14(10), 2931-2953. https://doi.org/10.1038/s41596-019-0208-0

Fu, R., Yan, D., & Lu, H. (2011). Polymeric nanomaterials from combined click chemistry and controlled radical polymerization. Polymer Chemistry, 2(4), 835-841. https://doi.org/10.1039/C0PY00335E

Galdames, A. (2020). Application of zero-valent iron nanoparticles for environmental remediation: A review. Environmental Nanotechnology, Monitoring & Management, 14, 100336. https://doi.org/10.1016/j.enmm.2020.100336

Gomiero, T. (2016). Soil degradation, land scarcity and food security: Reviewing a complex challenge. Sustainability, 8(3), 281. https://doi.org/10.3390/su8030281

He, F., & Zhao, D. (2007). Manipulating the size and dispersibility of zerovalent iron nanoparticles by using carboxymethyl cellulose stabilizers. Environmental Science & Technology, 41(17), 6216–6221.

Kalambate, P. K., Ghodake, G. S., & Saratale, R. G. (2019). Core@shell nanomaterials-based sensing devices: A review. TrAC Trends in Analytical Chemistry, 110, 115-131. https://doi.org/10.1016/j.trac.2018.10.033

Khan, M., Naeem, M., Adnan, S., Wang, Q., & Khan, M. Y. (2021). Effects of nanoparticles on soil-plant system: A review. Environmental Nanotechnology, Monitoring & Management, 15, 100425.

Kumari, A., Yadav, S. K., & Yadav, S. C. (2010). Biodegradable polymeric nanoparticles based drug delivery systems. Colloids and Surfaces B: Biointerfaces, 75(1), 1-18. https://doi.org/10.1016/j.colsurfb.2009.09.001

Kumpiene, J., Lagerkvist, A., & Maurice, C. (2008). Stabilization of As, Cr, Cu, Pb and Zn in soil using amendments–A review. Waste Management, 28(1), 215-225. https://doi.org/10.1016/j.wasman.2006.12.012

Liang, W., & Zhang, D. (2022). Transformation of chromium (VI) by zero-valent iron nanoparticles: Mechanisms and environmental applications. Journal of Hazardous Materials, 424, 127430. https://doi.org/10.1016/j.jhazmat.2021.127430

Liang, X., & Zhao, D. (2014). Immobilization of arsenic in soil and groundwater using starch-stabilized magnetite nanoparticles. Environmental Pollution, 188, 56–63.

Ma, L. Q., Rao, G. N., & Logan, T. J. (1993). Chemical fractionation of cadmium, copper, nickel and zinc in contaminated soils. Journal of Environmental Quality, 22(1), 227-233. https://doi.org/10.2134/jeq1993.00472425002200010027x

Natural Resources Conservation Service. (2000). Contaminants and remedial options at petroleum-contaminated sites. United States Department of Agriculture. https://www.nrcs.usda.gov

Paneru, P., & Kumar, M. (2023). Development of size and shape dependent model for bandgap of semiconductor nanomaterials. Modern Physics Letters B, 37(29), 2350111.

Prakash, P., Sharma, S., Gupta, R., & Verma, P. (2023). Phytoremediation: A green approach to remove contaminants from soil and water. International Journal of Environmental Science and Technology, 20(4), 2235–2250.

Rajput, V., Minkina, T., Behal, A., Sushkova, S., & Mandzhieva, S. (2022). Impact of nanoparticles on soil properties and plant growth: A review. Ecotoxicology and Environmental Safety, 239, 113589.

Robinson, B. H., Bischof, H., & Stoll, A. (2019). The role of amendment agents in heavy metal phytoremediation. Environmental Pollution, 248, 315-322. https://doi.org/10.1016/j.envpol.2019.02.084

Roca, A. G., Costo, R., & Rebolledo, A. F. (2019). Design strategies for shape-controlled magnetic iron oxide nanoparticles. Advanced Drug Delivery Reviews, 138, 68-104. https://doi.org/10.1016/j.addr.2018.12.008

Sathish, T., Ahalya, N., Thirunavukkarasu, M., Senthil, T. S., Hussain, Z., Haque Siddiqui, M. I., Panchal, H., & Kumar Sadasivuni, K. (2024). A comprehensive review on the novel approaches using nanomaterials for the remediation of soil and water pollution. Alexandria Engineering Journal, 86, 373–385.

Sharma, V. P., & Shukla, S. (2018). Advance applications of nanomaterials: A review. Materials Today: Proceedings, 5(11), 24140-24143. https://doi.org/10.1016/j.matpr.2018.10.218

Singh, B. R., Krogstad, T., & Akhtar, K. (2001). Sorption–desorption behavior of heavy metals during phosphorus fertilization. Geoderma, 103(1–2), 87-97. https://doi.org/10.1016/S0016-7061(01)00070-9

Sohail, M. I., Khan, M. N., & Usman, M. (2019). Environmental application of nanomaterials: A promise to sustainable future. In M. Naushad (Ed.), Nanomaterials: Types, properties, recent advances and toxicity concerns (pp. 1-24). Elsevier. https://doi.org/10.1016/j.coesh.2021.100319

Su, H., Jing, L., & Zhang, P. (2010). Synthesis of large surface area $LaFeO_3$ nanoparticles by SBA-16 template method as high active visible photocatalysts. Journal of Nanoparticle Research, 12, 967-974. https://doi.org/10.1007/s11051-009-9678-3

Thomas, S., Grohens, Y., & Pottathara, Y. B. (Eds.). (2015). Ceramic nanoparticles: Fabrication methods and applications in drug delivery. Elsevier.

Tian, X., Jin, Y., & Pang, B. (2018). Functional magnetic hybrid nanomaterials for biomedical diagnosis and treatment. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 10(1), e1475. https://doi.org/10.1002/wnan.1475