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Soil Remediation by Nanotechnology: Valuating Materials, Mechanisms, and Environmental Impacts

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ABSTRACT: The rapid growth of the human population and industrial activities has resulted in considerable environmental degradation. Processes such as industrialization, mining, agriculture, and waste disposal introduce harmful chemicals that contaminate soil, groundwater, and surface waters. Consequently, soil remediation has become a critical priority for many nations, given that soil quality directly affects agriculture and public health. Nanotechnology presents promising solutions to the shortcomings of traditional soil remediation methods by offering innovative materials and mechanisms for the removal or neutralization of contaminants. This review intends to evaluate the use of nanotechnology in soil remediation, emphasizing the nanomaterials employed, their reaction mechanisms, and potential environmental effects. Nanomaterials like nano zero-valent iron, metal oxides, and carbon-based materials have shown effectiveness in immobilizing, degrading, or extracting pollutants from soil and water through processes such as adsorption, photocatalysis, and filtration. However, certain nanomaterials raise concerns about toxicity and bioaccumulation, which may negatively affect ecosystems and human health. Therefore, additional research is needed to confirm the safety, compatibility, and sustainability of these technologies. This review also identifies significant challenges in the implementation of nanotechnologies for soil remediation and examines future directions and recommendations for addressing these challenges.

KEYWORDS: Soil remediation; environment pollution; nanotechnology; nanomaterials.

1. Introduction

A common consequence of rapid industrialization is the contamination of soil and groundwater which are valuable limited resources. Anthropogenic activities such as agriculture, mining, fossil fuel combustion, landfills and manufacturing processes have left many areas polluted with harsh contaminants including heavy metals, polycyclic aromatic hydrocarbons, pesticides, polyfluoroalkyl substances and combined pollutants [1]. Many of these contaminants are toxic in excess and often persist in the environment, either in their original form or their subsequent forms as a result of various factors affecting their mobility in the environment. Mechanisms of fate and transport of contaminants in the environment are governed by chemical, physical and biological factors, and processes [2]. It is well known that many of these pollutants have adverse impacts on human and environmental receptors, for instance, soil productivity, water quality, ecosystems, and human health [3]. Consequently, industrial and environmental laws have been implemented to make soil and water remediation mandatory to preserve the environment and protect human health from the adverse impacts of pollution. Conventional methods for soil and groundwater remediation have been developed and commonly applied includes solidification, soil washing, precipitation, extraction, thermal treatment, and phytoremediation [4–6]. However, many of these methods are very costly, time consuming, labour intensive, and ultimately ineffective at total removal of pollutants from soil and groundwater. For instance, it is challenging to continually monitor in-situ soil remediation efforts and also to achieve adequate mixing of the reagents with the contaminants [1].

Novel yet sustainable techniques and materials are continually in demand to counteract the increasingly complex environmental issues which arise from anthropogenic activities. Nanotechnology is a fast-emerging sector of innovative research and design with vast applications in the fields of agriculture, environmental sciences, medicine, materials, and energy (Figure 1). Nanotechnology refers to the use of molecular matter ranging from 1-100 nm for the development of structures and systems with advanced characteristics due to their small size [7]. Favourable characteristics include optimised energy conservation, antibacterial properties, improved structural strength and self-cleaning surfaces which all contribute to the effectiveness of nanomaterials in their various applications. Innovations in nanotechnology have many applications in soil and water remediation. For instance, nanomaterials are used as sensors for pollutant monitoring due to high specific surface which results in high accuracy, selectivity, sensitivity and time efficiency. Other nanomaterials applied in soil remediation such as ferrous and carbonaceous materials are effective due to their suitable surface chemistry, short molecular diffusion distance, uniform molecular dispersion and adjustable pore size making them suitable for in situ remediation [8].

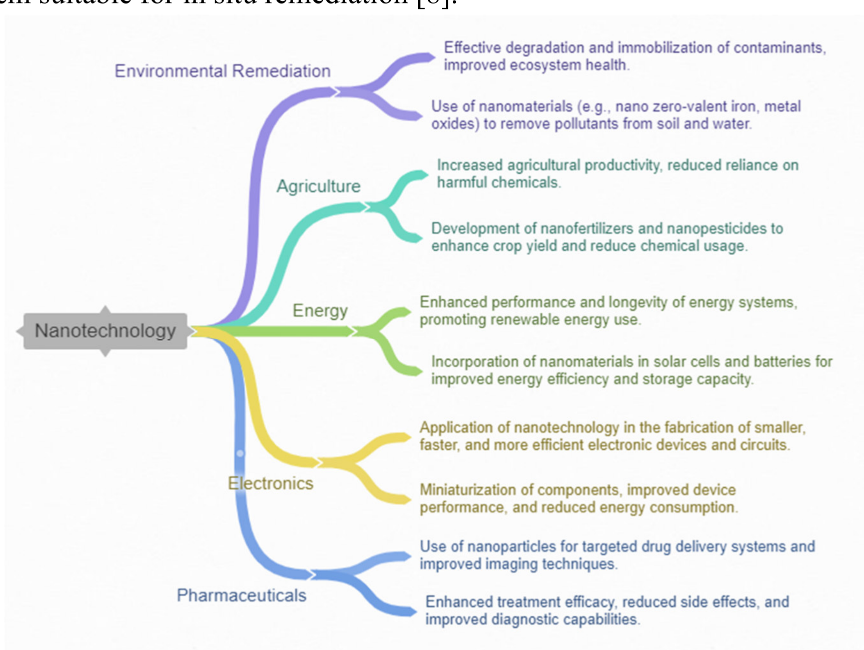

Figure 1. Common applications of nanotechnologies.

Compared to the conventional methods, nanotechnology has more favourable properties and can even improve soil fertility and crop yields. However, drawbacks such as complex preparation procedures and environmental impacts mean that more research is required to improve the application of nanomaterials. This present work aims to review the current status of nanotechnology applications especially in soil remediation and main challenges encountered in this field. Different nanomaterials and methods are discussed based on desk study of relevant research literature published during the period 2007-2022. Finally, future prospects of the nanotechnologies are provided with regards to the major challenges encountered.

2. Current Status of Nanotechnology for Soil Remediation

Soil remediation is considered top priority in developed and developing countries since agriculture and food security is directly dependent on the soil quality (Table 1). Toxic contaminants such as heavy metals and aromatic hydrocarbons can be transferred through ground water across the soil and taken up by crops, consequently entering the food chain where it can bioaccumulate. Therefore, novel solutions such as nanotechnology are in high demand since many human activities continue to pollute the environment at an alarming rate. In the recent decades, nanotechnology has been the focus of numerous scientific studies. Many nanomaterials have been identified, investigated, and developed to create small-scale structures and systems with optimised characteristics. From 2003 to 2013, Kumar Das et al. [9] observed through extensive desk study that majority of the publications and findings related to nanotechnology were being contributed by USA, China, Germany, Japan and Korea, respectively. In addition, since before 2012 nanotechnology products have been available in the market, with an estimation of about 3-4 new products being released every week. According to Gonçalves ~~(2016),~~[10], zero valent iron nanoparticles have already been implemented for soil remediation and gained a good reputation in some regions of Europe, United States and Japan. On the other hand, nanotechnologies are still in development phase such as in Portugal. Ahmed et al. ~~(2021)~~[11] stated that the favourable characteristics such as reduced reaction time and long-term efficiency have given nanomaterials as a promising reputation of replacing the harmful chemicals traditionally applied for soil and groundwater remediation.

Heavy metals are one of the most concerning pollutants due to their high toxicity and potential to bioaccumulate in the environment. Though heavy metals are naturally occurring in the environment due to geological processes, their concentrations in soils have drastically increased over the decades as a direct result of human activities like mining, industry, agriculture and traffic [7]. Currently, the use of nanomaterials is considered one of the most efficient solutions to remediating heavy metal contaminated sites. Widely applied nanomaterials for immobilization of heavy metals in soil include mainly zerovalent Iron, Iron oxides and nanocomposites such as graphene oxide and bimetallic nanoparticles. Agricultural yields are undeniably dependent on the physical, chemical and biological properties of the soil. Aside from removal of toxic pollutants, Liu et al. [12] also suggested that nanotechnology could improve food production, nutrition quality and agriculture as a whole. Due to their antimicrobial properties, nanomaterials have also been applied in the production of pesticides, biosensors and even fertilizers [13].

However, it should be noted that many of the existing studies based their investigations on laboratory experiments rather than field trials, and therefore more research is required to optimize dosage, safety, reliability and reproducibility of nanomaterials [11]. Another major challenge is that it has become increasingly evident that nanomaterials are potentially toxic to the environment, having negative impacts on plants, animals, and the ecosystem in general.

Furthermore, large scale production of such nanomaterials can be expected to generate large amounts of waste which could ironically pollute the environment elsewhere thus defeating the initial purpose of environmental remediation [9].

Table 1. Current status of nanotechnology for soil remediation.

Aspect	Details	Implications	References
Priority of Soil Remediation	Soil remediation is a top priority in both developed and developing countries due to its impact on agriculture and food security.	Contaminated soil affects crop quality and food safety, posing risks to public health.	[9]
Contaminants	– Toxic contaminants like heavy metals and aromatic hydrocarbons can contaminate soil and groundwater, entering the food chain and bioaccumulating. – Heavy metals are highly toxic and can bioaccumulate, with increasing concentrations in soils due to mining, industry, and agriculture. – Nanomaterials may be toxic to plants, animals, and ecosystems; large-scale production could generate waste that defeats remediation efforts.	– Increased human health risks due to the consumption of contaminated crops. – Acknowledges the persistent environmental and health challenges posed by heavy metal contamination. – Warns against the potential adverse effects of nanotechnology on environmental health and ecosystem balance.	[7, 9]
Demand for Nanotechnology	There is a high demand for novel solutions like nanotechnology due to ongoing environmental pollution from human activities.	Nanotechnology offers innovative solutions to remediate contaminated soils.	[9]
Market Availability	Nanotechnology products have been available since before 2012, with an estimated 3-4 new products released weekly.	Indicates rapid advancement and commercialization of nanotechnology in soil remediation.	
Current Development and Application	– Zero valent iron nanoparticles are used for soil remediation and have gained a good reputation in Europe, the USA, and Japan. – Nanotechnologies are still in the development phase in some regions, such as Portugal. – Widely used nanomaterials include zero valent iron, iron oxides, graphene oxide, and bimetallic nanoparticles for immobilizing heavy metals. – Nanomaterials have antimicrobial properties and are used in pesticides, biosensors, and fertilizers. – Nanomaterials are recognized for their reduced reaction time and long-term efficiency, making them promising alternatives to harmful traditional chemicals. – Nanotechnology could improve food production, nutrition quality, and overall agricultural practices.	– Demonstrates successful application of nanotechnology in addressing soil contamination. – Reflects the varying stages of nanotechnology implementation globally. – Offers effective solutions for remediating heavy metal-contaminated sites, improving soil quality. – Expands the role of nanotechnology in agricultural productivity and environmental protection. – Potential to significantly enhance the effectiveness of soil and groundwater remediation efforts. Enhances agricultural sustainability and food security.	[10–13]
Research Limitations	Most existing studies are based on laboratory experiments, highlighting the need for more field trials to optimize safety and reproducibility.	Identifies the necessity for practical applications and validations in real-world scenarios.	[11]

3. Nanomaterials

Nanomaterials are reactive engineered materials ranging from a dimension 1 to 100nm which can be applied to degrade, transform, remediate or detoxify environmental pollutants [9]. Their effectiveness depends on factors such as the method of preparation, their physiochemical characteristics, and their combability with the target contaminant. Commonly used nanomaterials can be classified as organic, such as carbonaceous materials, and inorganic, like metal oxides, bimetallic nanoparticles and noble metals. Inorganic nanomaterials including metals, noble metals, and metal oxides possess characteristics such as thermal conductivity, wide surface area and chemical stability thus making them effective at removal of heavy metals such as lead and cadmium [14]. Zero-Valent Iron (ZVI) nanoparticles are highly reactive due to high surface area to mass ratio, and act as permeable reactive barriers by immobilizing and treating pollutants [7]. Gonçalves [10] conducted a field experiment to test the efficiency of in situ soil remediation using Zero Valent Iron as the nanomaterial. The site selected was an old industrial complex area which was know to be contaminated with sulfuric acid, fertilizers, Zinc, Copper and Lead. After injection of the nanomaterial to the contaminated soil, positive results were observed whereby the pollutant concentrations were all reduced by 60% approximately over the whole reaction time. Furthermore, in their extensive review of the applications of nanomaterials for remediation of arsenic contaminated soil, Alikokht et al. [8] remarked that metal oxides can achieve over 80% removal of arsenic from soil or groundwater, is relatively easy to prepare and is easily recovered due to its magnetic properties. Investigations have also shown that noble metal nanoparticles such as silver and gold are antibacterial and antifungal making them good disinfectants for contaminated water and soil [9, 15]. Silica is another inorganic nanomaterial with the useful properties that can be applied for immobilization and removal of heavy metals and polycyclic aromatic hydrocarbons, and even certain contaminants in their gaseous state [16].

Organic nanomaterials are commonly used for soil remediation due to the favourable properties. Aside from high surface area to volume ratio, they are also highly stable while being catalytic, and widely available compared other nanomaterials such as noble metals [17]. Graphene and carbon nanotubes are carbon-based nanomaterials which through their high adsorption capacity can sequester both organic and inorganic pollutants from the environment. Graphene and graphene oxides have high specific surface area, thermal conductivity and high mechanical strength making it very effective for wastewater remediation especially. However, many challenges still hinder the maximum implementation of graphene nanomaterials, for example technical issues like separation, reusability, cost effectiveness and management of environmental impacts. Carbon nanotubes differ from graphene mainly in their molecular structure, with the nanotubes being cylindrical and hollow in structure, with varying numbers of carbon layers. Carbon nanotubes are considered more effective at adsorption compared to the traditional activated carbon [18], and have antibacterial properties, capable of destroying bacteria such as *E. coli* from contaminated water. This material can be combined with titanium dioxide to undergo photocatalytic degradation reactions to eliminate contaminants, and has a wide variety of applications such as sensors, membranes, catalysts, and adsorbents [9, 19].

4. Soil remediation mechanisms involving nanotechnology

Nanomaterials can be applied either in situ or ex situ for soil remediation depending on the site conditions, type of contaminants, and extent of or severity of contamination. Elimination, immobilization, and removal of contaminants by applying nanomaterials is achieved by means of different physiochemical mechanisms. Such mechanisms for applying nanomaterials to contaminated soil includes adsorption, photocatalysis, filtration, immobilization, and nano-bioremediation amongst many others. Such techniques will be further discussed in this section, and summarized in Table 2.

Table 2. Summary of nanotechnology mechanisms.

Mechanism	Nanomaterials involved	Advantages	Disadvantages	Reference
Adsorption	Carbon-based nanomaterials such as graphene, activated carbon and carbon nanotubes.	Cost effective, Effective for removal of both organic and inorganic pollutants, easy operation.	Time consuming, energy intensive to produce the nanomaterials, and difficult to recover from solution.	[20]
Photocatalysis	Metal oxides such as titanium dioxide, zirconium dioxide, and iron dioxide.	Capable of removal of pollutants even at low concentrations.	Energy and labour-intensive process. Costly and requires regular maintenance.	[7, 20]
Filtration	Membrane filtration, ultra-filtration is applied for removal of nanoscale contaminants.	Capable of removing various types of pollutants according to size.	Costly, energy intensive, and regular maintenance required.	[20, 21]

4.1.Adsorption.

Mainly carbon-based nanomaterials are applied in the adsorption mechanism due to their excellent adsorption capacity, large surface area, mechanical strength, and ability to attach to a variety of functional groups. Through the adsorption process, contaminants such as heavy metals, polycyclic aromatic hydrocarbons, and chemical dyes in solid, liquid and even gaseous phase can be removed from the environment. According to Artioli [22], adsorption can be described as a surface process whereby a 'molecule from a fluid bulk is transferred to a solid surface', and can be due to both physical and chemical forces. Van der Waals interactions are the main forces responsible for physical adsorption, whereas formation of chemical bonds such as covalent bonds govern the principles of chemical adsorption [22]. Cost effectiveness is a major benefit of using carbon-based nanoparticles in the adsorption process, as well as the wide variety of options of possible nanomaterials available and those still in development. Furthermore, due to their compatibility to multiple functional groups, commercialized nanomaterials such as activated carbon are suitable for removal of various contaminants which may be simultaneously present or combined at the polluted site [23]. Also, carbon-based nanomaterials are effective disinfectants through the adsorption mechanism, as described by Lakshmi et al. [24] who actually produced the nanomaterials from biowastes. However, production of nanomaterials such as activated carbon is often times energy intensive, unless a renewable energy source is factored in [7]. Many of the nanomaterials have also been considered expensive to develop, have poor potential for recovery and reuse, are inefficient and have short lifespan [23].

4.2.*Photocatalysis*.

Photocatalysis is the process whereby UV light or sunlight is applied to contaminated water and soil in the presence of reactants known as photocatalysts to induce the degradation of both organic and inorganic pollutants [1]. The photocatalysts are highly reactive hydroxyl and superoxide radicals used to initiate the removal of halogenated organic compounds and heavy metals. Titanium dioxide, iron oxide and zirconium dioxide is considered an ideal photocatalyst due to its suitable bandgap, particle size, high porosity, high surface area to volume ratio, and good stability [7, 25, 26]. Generally, metallic photocatalysts are doped to improve their efficiency by changing the energy gap, increase the active sites, improving any structural defects which will improve their performance under UV light conditions. Some of the advantages of photocatalysis is that it is effective even at low concentrations of contaminants, and photocatalysts typically have a long-life span [23]. On the other hand, drawbacks of this mechanism include poor in situ remediation since UV light cannot penetrate thoroughly, high energy consumption, regular maintenance of UV lamp equipment high cost, and labour intensive [7].

4.3.Filtration.

Filtration involves the use of a filter or membrane to separate one entity from the other. The main criteria for this technique are the size of the of the target particles which are to be removed from the bulk of the solution or mixture. Membrane filtration, microfiltration and reverse osmosis are several types of filtration processes that have been developed to separate pollutants such as heavy metal ions from solutions [27]. Standard filtration is relatively simple to operate; however, membrane filtration is more challenging to operate and maintain due to the specific conditions which must be maintained to prevent a phenomenon called fouling. Membrane filtration is often energy intensive since high pressures are required to ensure fluid flow across the membrane. Aside from high operating costs, it has high maintenance costs since regular back washing and membrane cleaning is required to prevent clogging of the pores [21].

5. Challenges and Future Prospective

Although nanotechnology presents innovative and efficient solutions for remediating contaminated soils, it also has certain drawbacks which have prevented the large-scale commercialization of nanomaterials and complete replacement of conventional remediation methods. Many nanomaterials are still under experimental phase, with aspects such as their fate and transport, toxicity, impacts in the environment and public health safety still under investigation. Success of soil remediation strategies are dependent on factors such as physical and chemical properties of the soil, types of vegetation or ecosystem of the site and characteristics of the remedial nanomaterials [12]. Therefore, much research and consideration are required to ensure the correct nanotechnology is applied to treat the contaminant of concern. The appropriate dosage, safety thresholds and methods of application. Some of the reported negative environmental impacts of nanomaterials include the risk for bioaccumulation in soil, flora, fauna and another biota [28]. Zhang et al. [29] even remarked that certain nanomaterials containing copper stunted germination of seeds, growth of roots and shoots, and also the ability to photosynthesize. Exposure to high concentrations of certain nanomaterials through digestion, inhalation and skin contact could lead to serious health consequences such as diseases, organ damage, and even genetic defects [30]. Such concerns should be addressed by increasing the efforts to develop safer nanotechnology designs, increase the biocompatibility and sustainability of nanomaterials, and generally, to gain better understanding of their implications in the environment.

Furthermore, a recent review about the use of nanomaterials for remediation of dye-contaminated sites, it was observed that few studies have been conducted to explore the regeneration methods for nanomaterials which is one of the factors impeding large scale commercialization. Therefore, more research is required to investigate the potential for safe, cost-effective recovery and reuse strategies for the different nanomaterials, as this will impact the cost of raw materials and overall processes (Tan et al., 2015). Alternatively, the continuous development and production of green nanocomposites from plants is strongly encourage because they are simple, widely available, environmentally friendly and cost effective [31–33].

Social and environmental sustainability should be considered priority and should not be compromised to achieve maximum remedial efficiency at the cost of the environment and public health quality. Governments should shift their focus strong regulation policy to ensure safety and ethics are maintained in the current and future applications of nanotechnologies. Policy is an important tool for maintaining environmental and socioeconomic wellbeing. Since majority of the studies conducted laboratory experiments, future research should focus on field trials to evaluate the real-world implication of nanomaterials [34, 35].

6. Conclusion

Since the 1980s, nanotechnology has gained increasing popularity in various fields such as agriculture, pharmaceuticals, energy, and environmental remediation. The focus of this present work was to review the applications of nanotechnology in soil remediation. Nanomaterials have many favourable characteristics such as high specific surface area, high area to volume ratio, high porosity, and good mobility to move through pores between soil particles. Currently, several nanomaterials have already been commercialized and implemented for remediation of contaminated sites. For instance, nano zero valent iron, graphene, activated carbon, metal oxides and noble metals were considered in terms of their applications and efficiency. Different physical and chemical mechanisms are involved in the application of these nanomaterials depending on the type of contaminants to be removed and characteristics of the site. Since there is also concern about the safety of nanomaterials, more research is required to further improve the social and environmental impacts of nanomaterial assisted soil remediation. All in all, nanotechnology is still a very promising field of research with real potential to benefit the environment.

Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Carol Emilly Hoareau: conceptualization, data analysis, drafting of the manuscript, methodology and interpretation of the results. Clementine Kabeya: research design, data collection, interpretation, writing and revision.

References

[1] Qian, Y.; Qin, C.; Chen, M.; Lin, S. (2020). Nanotechnology in soil remediation − applications vs. implications. *Ecotoxicology and Environmental Safety*, *201*, 110815. https://doi.org/10.1016/j.ecoenv.2020.110815.

[2] Carrillo-González, R.; Šimůnek, J.; Sauvé, S.; Adriano, D. (2006). Mechanisms and pathways of trace element mobility in soils. *Advances in Agronomy, 91*, 111–178. https://doi.org/10.1016/S0065-2113(06)91003-7.

[3] Mitra, S.; Chakraborty, A.J.; Tareq, A.M.; Emran, T.B.; Nainu, F.; Khusro, A.; Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University - Science*, *34*(3), 101865. https://doi.org/10.1016/j.jksus.2022.101865.

[4] Makino, T.; Kamiya, T.; Takano, H.; Itou, T.; Sekiya, N.; Sasaki, K.; Sugahara, K. (2007). Remediation of cadmium-contaminated paddy soils by washing with calcium chloride: Verification of on-site washing. *Environmental Pollution*, *147*(1), 112–119. https://doi.org/10.1016/j.envpol.2006.08.037.

[5] Wang, H.; Liang, X.; Wang, J.; Jiao, S.; Xue, D. (2020). Multifunctional inorganic nanomaterials for energy applications. *Nanoscale*, *12*(1), 14-42.

[6] Zhao, F.-J.; Ma, Y.; Zhu, Y.-G.; Tang, Z.; McGrath, S.P. (2015). Soil contamination in China: Current status and mitigation strategies. *Environmental Science & Technology*, *49*(2), 750–759. https://doi.org/10.1021/es5047099.

[7] Ekrami, E.; Pouresmaieli, M.; Hashemiyoon, E.S.; Noorbakhsh, N.; Mahmoudifard, M. (2022). Nanotechnology: A sustainable solution for heavy metals remediation. *Environmental Nanotechnology, Monitoring & Management*, *18*, 100718. https://doi.org/10.1016/j.enmm.2022.100718.

[8] Alidokht, L.; Anastopoulos, I.; Ntarlagiannis, D.; Soupios, P.; Tawabini, B.; Kalderis, D.; Khataee, A. (2021). Recent advances in the application of nanomaterials for the remediation of arsenic-contaminated water and soil. *Journal of Environmental Chemical Engineering*, *9*(4), 105533. https://doi.org/10.1016/j.jece.2021.105533.

[9] Kumar Das, P.; Mohanty, C.; Krishna Purohit, G.; Mishra, S.; Palo, S. (2022). Nanoparticle assisted environmental remediation: Applications, toxicological implications and recommendations for a sustainable environment. *Environmental Nanotechnology, Monitoring & Management*, *18*, 100679. https://doi.org/10.1016/j.enmm.2022.100679.

[10] Gonçalves, J. R. (2016). The soil and groundwater remediation with zero valent iron nanoparticles. *Procedia Engineering*, *143*, 1268–1275. https://doi.org/10.1016/j.proeng.2016.06.122.

[11] Ahmed, T.; Noman, M.; Ijaz, M.; Ali, S.; Rizwan, M.; Ijaz, U.; Li, B. (2021). Current trends and future prospective in nanoremediation of heavy metals contaminated soils: A way forward towards sustainable agriculture. *Ecotoxicology and Environmental Safety*, *227*, 112888. https://doi.org/10.1016/j.ecoenv.2021.112888.

[12] Liu, Y.; Chen, H.; Zhu, N.; Zhang, J.; Li, Y.; Xu, D.; Zhao, J. (2022). Detection and remediation of mercury contaminated environment by nanotechnology: Progress and challenges. *Environmental Pollution*, *293*, 118557. https://doi.org/10.1016/j.envpol.2021.118557.

[13] Usman, M.; Farooq, M.; Wakeel, A.; Nawaz, A.; Cheema, S. A.; Rehman, H.U.; Sanaullah, M. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of The Total Environment*, *721*, 137778. https://doi.org/10.1016/j.scitotenv.2020.137778.

[14] Wang, Q.; Guo, S.; Ali, M.; Song, X.; Tang, Z.; Zhang, Z.; Luo, Y. (2022). Thermally enhanced bioremediation: A review of the fundamentals and applications in soil and groundwater remediation. *Journal of Hazardous Materials*, *433*, 128749. https://doi.org/10.1016/j.jhazmat.2022.128749.

[15] Lisha, K.; Pradeep, T. (2009). Towards a practical solution for removing inorganic mercury from drinking water using gold nanoparticles. *Gold Bulletin*, *42*(2), 144–152. http://doi.org/10.1007/BF03214924.

[16] Guerra, F.D.; Campbell, M.L.; Whitehead, D.C.; Alexis, F. (2017). Tunable properties of functional nanoparticles for efficient capture of VOCs. *ChemistrySelect*, *2*(31), 9888–9888. http://doi.org/10.1002/slct.201702287.

[17] Madhura, L.; Singh, S.; Kanchi, S.; Sabela, M.; Bisetty, K. (2019). Nanotechnology-based water quality management for wastewater treatment. *Environmental Chemistry Letters*, *17*(1), 65–121. http://doi.org/10.1007/s10311-018-0778-8.

[18] Jun, L.Y.; Mubarak, N.M.; Yee, M.J.; Yon, L.S.; Bing, C.H.; Khalid, M.; Abdullah, E.C. (2018). An overview of functionalised carbon nanomaterial for organic pollutant removal. *Journal of Industrial and Engineering Chemistry*, *67*, 175-186. https://doi.org/10.1016/j.jiec.2018.06.028.

[19] Das, P.K. (2018). Phytoremediation and nanoremediation: Emerging techniques for treatment of acid mine drainage water. *Defence Life Science Journal*, *3*(2), 190–196.

[20] Alharbi, N.S.; Hu, B.; Hayat, T.; Rabah, S.O.; Alsaedi, A.; Zhuang, L.; Wang, X. (2020). Efficient elimination of environmental pollutants through sorption-reduction and photocatalytic degradation using nanomaterials. *Frontiers of Chemical Science and Engineering*, *14*(6), 1124–1135. https://doi.org/10.1007/s11705-020-1923-z.

[21] Adeleye, A.S.; Conway, J.R.; Garner, K.; Huang, Y.; Su, Y.; Keller, A.A. (2016). Engineered nanomaterials for water treatment and remediation: Costs, benefits, and applicability. *Chemical Engineering Journal*, *286*, 640–662. http://doi.org/10.1016/j.cej.2015.10.105.

[22] Artioli, Y. (2008). Adsorption. In Encyclopedia of Ecology; Jørgensen S.E., Fath, B.D., Eds.; Academic Press: Cambridge, USA, pp. 60–65. http://doi.org/10.1016/B978-008045405-4.00252-4.

[23] Tan, K.B.; Vakili, M.; Horri, B.A.; Poh, P.E.; Abdullah, A.Z.; Salamatinia, B. (2015). Adsorption of dyes by nanomaterials: Recent developments and adsorption mechanisms. *Separation and Purification Technology*, *150*, 229–242. http://doi.org/10.1016/j.seppur.2015.07.009.

[24] Lakshmi, S.D.; Avti, P.K.; Hegde, G. (2018). Activated carbon nanoparticles from biowaste as new generation antimicrobial agents: A review. *Nano-Structures & Nano-Objects*, *16*, 306–321. http://doi.org/10.1016/j.nanoso.2018.08.001.

[25] Aghabeygi, S.; Khademi-Shamami, M. (2018). ZnO/ZrO_2 nanocomposite: Sonosynthesis, characterization and its application for wastewater treatment. *Ultrasonics Sonochemistry*, *41*, 458–465. http://doi.org/10.1016/j.ultsonch.2017.09.020.

[26] Mazarji, M.; Minkina, T.; Sushkova, S.; Mandzhieva, S.; Bidhendi, G.N.; Barakhov, A.; Bhatnagar, A. (2021). Effect of nanomaterials on remediation of polycyclic aromatic hydrocarbons-contaminated soils: A review. *Journal of Environmental Management*, *284*, 112023. http://doi.org/10.1016/j.jenvman.2021.112023.

[27] Fu, F.; Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management*, *92*(3), 407–418. http://doi.org/10.1016/j.jenvman.2010.11.011.

[28] Deng, R.; Lin, D.; Zhu, L.; Majumdar, S.; White, J.C.; Gardea-Torresdey, J.L.; Xing, B. (2017). Nanoparticle interactions with co-existing contaminants: joint toxicity, bioaccumulation and risk. *Nanotoxicology*, *11*(5), 591–612. http://doi.org/10.1080/17435390.2017.1343404.

[29] Zhang, Z.; Ke, M.; Qu, Q.; Peijnenburg, W.J.G.M.; Lu, T.; Zhang, Q.; Qian, H. (2018). Impact of copper nanoparticles and ionic copper exposure on wheat (*Triticum aestivum* L.) root morphology and antioxidant response. *Environmental Pollution*, *239*, 689–697. http://doi.org/10.1016/j.envpol.2018.04.066.

[30] Iavicoli, I.; Leso, V.; Beezhold, D.H.; Shvedova, A.A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and Applied Pharmacology*, *329*, 96–111. http://doi.org/10.1016/j.taap.2017.05.025.

[31] Hussain, A.; Rehman, F.; Rafeeq, H.; Waqas, M.; Asghar, A.; Afsheen, N.; Iqbal, H.M.N. (2022). In-situ, Ex-situ, and nano-remediation strategies to treat polluted soil, water, and air – A review. *Chemosphere*, *289*, 133252. http://doi.org/10.1016/j.chemosphere.2021.133252.

[32] Lashen, Z.M.; Shams, M.S.; El-Sheshtawy, H.S.; Slaný, M.; Antoniadis, V.; Yang, X.; Elmahdy, S. M. (2022). Remediation of Cd and Cu contaminated water and soil using novel nanomaterials derived from sugar beet processing- and clay brick factory-solid wastes. *Journal of Hazardous Materials*, *428*, 128205. http://doi.org/10.1016/j.jhazmat.2021.128205.

[33] Yadav, N.; Garg, V.K.; Chhillar, A.K.; Rana, J.S. (2021). Detection and remediation of pollutants to maintain ecosustainability employing nanotechnology: A review. *Chemosphere*, *280*, 130792. http://doi.org/10.1016/j.chemosphere.2021.130792.

[34] Kumar, N.; Kandasami, R.K.; Singh, S. (2022). Effective utilization of natural fibres (coir and jute) for sustainable low-volume rural road construction – A critical review. *Construction and Building Materials*, *347*, 128606. http://doi.org/10.1016/j.conbuildmat.2022.128606.

[35] Mishra, M.; Dashora, K.; Srivastava, A.; Fasake, V.D.; Nag, R.H. (2019). Prospects, challenges and need for regulation of nanotechnology with special reference to India. *Ecotoxicology and Environmental Safety*, *171*, 677–682. http://doi.org/10.1016/j.ecoenv.2018.12.085.