

A Comprehensive Review on Remediation Techniques for Heavy Metal-Contaminated Soils

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Abstract- Due to the increasing industrial sector and era of urbanization, today there is a rising number of heavy metals and organic pollutants found in the soil. Soil erosion, pollution, salinization, and the continuous accumulation of soil fertility, biological and chemical properties, and physical structure are leading to an increase in toxic metals. This is not just a problem for a specific area but is becoming a serious global issue. According to global reports, it has been found that more than 50% of available agricultural land at 10 million sites around the world is contaminated with heavy metals. This is not only increasing the presence of heavy metals in the soil but also in the environment. Contaminated soil is more commonly observed in developed countries, while India, being a developing nation, is facing a growing presence of heavy metals in the soil due to ongoing development, industrialization, and urbanization plans.

Keywords: Soil contamination, Phytoremediation, Nanoremediation, Heavy metals, Soil pollutants.

I. INTRODUCTION

Heavy metals are the most important soil contaminants in the environment. Heavy metals are the integrated components of the biosphere and thus occur naturally in soils and plants. Heavy metals (Cd, Cr, Cu, Hg, Pb, and Zn) have occurred widely because of human, agricultural, and industrial activities, which are responsible for the contamination of soils. Some of these metals are micronutrients that are necessary for plant growth, such as Zn, Cu, Mn, Ni, and Co, while others have unknown biological functions, such as Cd and Pb. Agricultural activities involving the addition of inorganic fertilizers, insecticides, pesticides, and amendments to the soil for increasing productivity are responsible for soil contamination/pollution. Water used for irrigation and the release of industrial effluents in water resources pollutes the soil with solid wastes, heavy metals, and several other organic and inorganic substances.

Reclamation of such contaminated soils through the phytoremediation method was found to be the cheapest and an effective method for extraction or removal of pollutants from contaminated soils. This not only damages the biological molecules of the soil but also makes the soil's microorganisms toxic. Currently, organic pollutants play a significant role in contaminating the land, as do heavy metals. Both are

very serious issues that, in the future, pose a toxic threat to plants, animals, and human life worldwide. The presence of heavy metal pollution from various sources constitutes a serious risk to both human health and the environment because of their inability to biodegrade and their tendency to build up in living organisms. Toxic heavy metals, including Cr (IV), Cd (II), Ni (II), As (III and V), Pb (II), Cu (II), Zn (II), Sb (II), Hg (II), and Se (II), pose significant hazards to living beings. Over time, these metals can accumulate in the body, resulting in severe health issues. Cr (IV) is known to be carcinogenic and can lead to lung cancer. Cd (II) negatively impacts the kidneys and can result in renal failure. Ni (II) is recognized as a carcinogen and has the potential to cause lung and nasal cancers. As (III and V) are extremely hazardous and may result in skin lesions, breathing problems, and cancer. Pb (II) impacts the nervous system and may lead to developmental delays in young children. Cu (II) has the potential to harm the liver and kidneys. Zn (II) toxicity can result in gastrointestinal problems. Sb (II) may cause respiratory complications and liver harm. Hg (II) affects the nervous system and can result in neurological disorders.

Objectives

The study aims to focus on literature that determines the contamination of heavy metals in soil.

- To determine the heavy metal components by physical and chemical parameters of collected soil samples.
- To analyze the effect of different remediation methods on soil samples.
- To analyze the correlation among physical and chemical parameters of soil after remediation.

II. LITERATURE REVIEWS

Friberg et al. 1993. This paper gives an overview of several important aspects of biological monitoring but does not provide detailed information on metals. The main sources of Ni are wastewaters of electroplating, battery, motor vehicle, petroleum, steel, and aircraft industries. The major users of Ni, around 40% of its production, are the steel industry, the battery industry, and the production of alloys.[1]

Nicholson et al. (2003) presents an inventory of selected heavy metals, i.e., Zn, Cu, Ni, Pb, Cd, Cr, As, and Hg, inputs to agricultural soils in England and Wales in 2000. The major sources of heavy metal contamination included atmospheric deposition, sewage sludge, livestock manures, inorganic fertilizers and lime, agrochemicals, irrigation water, industrial by-product 'wastes,' and composts. The author identified that the prime source of heavy metal pollution in the whole agricultural land area was atmospheric deposition, ranging from 25% to 85% of total inputs. Livestock manures and sewage sludge were important sources of total Zn and Cu inputs estimated to be 37–40% and 8–17%, respectively. However, at individual field scale, sewage sludge, livestock manure, and industrial wastes have been estimated as the foremost cause of several metals where these materials are applied. The author envisages the preparation of an inventory of heavy metals to develop strategies for decreasing heavy metal inputs to agricultural land and effectively targeting guidelines to protect soils from high rates of heavy metal accumulation.[2]

Sharma et al. (2007) address lead as a potential pollutant among other heavy metals, which readily accumulates in soils and sediments. It is not considered an essential element for plants but gets easily absorbed by plants and at toxic levels shows several abnormal symptoms such as stunted growth,

chlorosis, and blackening of the root system, inhibits photosynthesis, and upsets mineral nutrition and water balance in addition to hormonal changes and adverse effects on membrane structure and permeability. The article also describes the mechanism of lead detoxification process and brings forth the concept of lead tolerance. The authors suggest phytoremediation and rhizofiltration technologies for cleaning of lead-contaminated soil.[3]

Iqbal et al. (2011) conducted their study on accumulation of heavy metals nickel, copper, cadmium, chromium, and lead in agricultural soils and plants irrigated by industrial wastewater in three selected regions. Their findings showed all soil samples were enriched with toxic metals but nickel and chromium were present at elevated levels. The spring seasonal plant showed a higher level of chromium among the selected heavy metals. The basic tendency of agricultural soil suits the combination of chromium (III) with oxide and hydroxide ions and the remaining chromium (VI) is taken up by the plants cultivated in this region. The authors recommended disposal of wastewater from industries after suitable treatment, lining of drain channels to prevent seepage of wastewater need for government and industrialist intervention to prevent any hazardous situation, and guidelines for reuse of wastewater.[4]

Zhang et al. (2013). This paper provides an overview on the impact of biochar on the environmental fate and mobility of heavy metals and organic pollutants in contaminated soils and its implication for remediation of contaminated soils. Further research directions are identified to ensure a safe and sustainable use of biochar as a soil amendment for remediation of contaminated soils. Growth and metabolism of plants are aided by a few metals like copper, zinc, chromium, iron, etc. When the concentration of heavy metals is higher than the admissible levels, the plants absorb and store it in the edible parts and create severe health hazards for human beings.[5]

Alloway (2013). The editor provides an account on heavy metals and metalloid sources in soils. The

chemistry of heavy metals and metalloids has been included as a separate chapter in this book. This book also discusses the methods for heavy metal and metalloid determination in soils. Both positive and negative impacts of heavy metals and metalloids on soil organisms have been discussed along with soil-plant relationship regarding heavy metals and metalloids. The bioavailability of metals to the plant and role of heavy metals as essential micronutrients have been addressed in this book. The chapter on critical load of heavy metal in soil signifies that soil, based on its utilization, has a certain capacity of heavy metal content in it, above which, if present, may cause adverse effect on plant and animals and is supposed to have toxic effect on the corresponding plant and animal species. The book discusses individually important heavy metals and metalloids in addition to other heavy metals and metalloids of potential environmental significance.[6]

Mathur and Kumar (2013). A physicochemical investigation of textile effluent was conducted in the soil samples of the Sanganer region. Sanganer is a place where textile dyeing and printing industries are present in large numbers. Water pollution is very prevalent in this area. This pollution is caused by the discharge of wastewater by activities like bleaching, dyeing, and printing. These effluents intrude on biotic components of the ecosystem. This study concludes that textile effluents should be treated before discharging into the ecosystem.[7]

Wuan et al. (2014). To moderate the risk factors of heavy metal contamination and all the associated risk factors, remediation of the contaminated soil is very significant. This remediation would make soil fit for agricultural production, provide food security, and reduce land tenure issues. Best available technological practices for remediating these heavy metals are immobilization, leaching of topsoil, and phytoremediation. This remediation can be used for the fields and for commercial practices, especially in the developing countries where environmental degradation has been caused due to urbanization, industrialization, and agriculture.[8]

Bhalerao et al. (2015) explains the importance of heavy metal nickel, which is an essential micronutrient for plant growth. The authors mention that nickel is the primary component of the enzyme urease utilized for nitrogen metabolism in higher plants. Nickel and its compounds have plenty of industrial and commercial uses. Rapid industrialization has escalated the emission of pollutants into the environment, including nickel and its compounds. Nickel is absorbed and redistributed in plants via cation and/or metal-ligand complex transport system. The study suggests that Ni is strongly phytotoxic at higher concentrations.

Ni is supposed to induce change in activity of antioxidant enzymes like superoxide dismutase (SOD), ascorbate peroxidase (APX), and catalase (CAT) in several plants. Nickel, according to this literature, strongly influences metabolic reactions in plants and is capable of generating reactive oxygen species (ROS), which may cause oxidative stress. Nickel in higher concentrations inhibits cell division at root meristem in nontolerant plants and retards plant growth. Studies have shown that nickel has negative impact on photosynthesis and respiration. High uptake of nickel induces decline in water content of dicot and monocot plants. This decline in water content in plants can be considered as an indicator for Ni toxicity in plants provided nickel concentration in plants is analyzed in general environmental conditions and nickel-induced environmental conditions.

Nickel is associated with protein inhibition, germination, and chlorophyll synthesis. Nickel has a dual character and complicated electronic chemistry, which acts as a barrier revealing toxicity mechanism in plants. This review paper summarizes the overview of the sources, essentiality, uptake and toxicity of nickel in plants. According to the authors, nickel pollution is a serious environmental concern, paving the way for research on phytoremediation. Further studies are required in future to comprehend the details at both biochemical and molecular levels for nickel tolerance of nickel hyperaccumulators.[9]

Garba et al. 2018 In this work the author investigates the physicochemical properties of spent engine oil

polluted soil sites in Bali and its environs and Taraba State, Nigeria. The result revealed the particle size distribution showing that polluted soils were categorized by relatively high sand content ranging from 30.2% to 80.2%, with an average mean of 58.08%; silt 15.3--65.1% (34.88%); and clay 3.0--11.6% (7.04%). The textural descriptions of soils from the study sites were mostly sandy loam. The main sources of Zn are atmospheric, agricultural, pharmaceutical, domestic, and industrial effluents. The major sources of industrial wastewaters are zinc smelters, zinc mining, battery, petroleum, toys, alloys, detergent, coal combustion, and steel industries.[10]

Waris et al. stated that reducing heavy metals from the soil is very important for the agriculture sector because in this era of increasing industrialization, where more and more chemicals are being used to enhance production capacity, the fertility of the earth is being diminished due to these chemicals, leading to a continuous decline in production capacity. Additionally, the crops produced during this process are also being contaminated due to these chemicals and heavy metals, resulting in a shorter shelf life for the grains. Furthermore, consuming these contaminated grains is causing severe diseases like cancer in the human body. We can use various methods to extract heavy metals from polluted land, including soil washing, encapsulation, nano-remediation, chemical extraction, chemical leaching, iron exchange, and precipitation. By utilizing these methods, we can reduce the toxic levels in the soil and boost the fertility of the earth.[11]

Singh et al. Remediation of heavy metal contaminated soils using different amendments and different species of Brassica. "<http://hdl.handle.net/10603/45175> (2013)."[12]

Reported that contaminated soil is very dangerous for our environment and human health because it plays a significant role in the food chain. Phytoremediation is a cost-effective plant-based approach through which we can prevent heavy metal components from entering the environment! In their investigation, they have reduced the levels of zinc, copper, and nickel from the soil with the help of

Brassica species. They also mentioned in their observations that in recent decades, heavy metal contamination of the earth has increased. The impact is greater around industrial areas, and various Brassica species can be utilized for its remediation. Using clotting agents like DTPA, zinc, copper, and nickel can be reduced from the earth.

Mulugeta et al. (2019). This study suggests quick intervention and close monitoring to arrest and solve the growing environmental pollution. Heavy metals are commonly found in textile effluents. The study was conducted on the effluents of the textile industries in Ethiopia. All the heavy metals did not have significant affluence for the environment. Heavy metals such as Pb, As, Cr, Zn, and Mn have been determined by FAAS and ICP-OES. The concentration of chromium was negligible.[13]

Li et al. (2019). In this study, author reviews the heavy metal contamination in soil and analyzes remediation techniques from the indoor dust of the Xinqiao mining area, Tongling, China, and the health risk of heavy metals like Cu, Pb, Zn, Ni, Co, Cd, and Cr. The indoor dust had higher parameters of heavy metals. Co was the only exception to that as the limits were lower when compared to other metals. The descending order of the heavy metal concentration is sequenced as cadmium, zinc, copper, and lead. Higher concentrations of heavy metals like Ni, Cr, Cd, and Co would result in cancer.[14]

Xiao et al. (2020) In this study, author explained the improved safety and applicability of phytoremediation combined with other repair approaches compared to common standalone approaches. Finally, we established a prospective research direction of phytoremediation combined with multi-technology repair strategy. In uranium mines of Zoige county in Sichuan Province, China, the concentration of heavy metals along with the moisture content and soil pH was analyzed. Heavy metal concentration was higher in the sample. The results show that the level of heavy metals was higher. Pollution of heavy metals was assessed based on the Igeo values. Igeo values were higher for As and U, moderately polluted value was obtained for

Cr and Mo, a negative value for Sr, and lower values for V and Zn. The results indicate that the soil is heavily polluted with As and U.[15]

Haider et al. (2021). Cadmium (Cd) is a nonessential trace element in plants, ubiquitous in the environment. Anthropogenic activities like disposal of urban refuse, smelting, mining, metal manufacturing, and application of synthetic phosphate fertilizers increase Cd concentration in environment. Cd is carcinogenic. In this manuscript, the authors reviewed sources of Cd contamination in the environment, soil factors influencing Cd intake, dynamics of Cd in soil rhizosphere, intake mechanisms, translocation, and toxicity of Cd in plants. In crop plants, toxicity of Cd lowers intake and translocation of nutrients and water, intensifies oxidative damage, interrupts plant metabolism, and inhibits plant morphology and physiology. The author also discusses defense mechanisms in plants against Cd toxicity and potential remediation approaches, including the use of biochar, mineral nutrients, compost, organic manure, growth regulators, and hormones, along with the application of phytoremediation, bioremediation, and chemical methods. The author documented this manuscript with a view to determine ecological significance of Cd stress in interdisciplinary studies and suggest principal remediation approaches to overcome Cd contamination in agricultural soils.[16]

Shah Jehan (2022). The soil in Hattar Industrial Estate located in Pakistan, was determined to be contaminated with heavy metal. The concentration of heavy metal(loids) was high in wastewater irrigated agriculture soil and waste-dumped soil sites. From the estimated heavy metal concentration pollution quantification factors, contamination factor, pollution load index, health risk factors for chronic and nonchronic cancer, and ecological risk factors were analyzed.[17]

Problem Identification

Heavy metals in soil are a significant environmental issue, especially in urban, industrial, and agricultural areas. These metals, when present in excess, can be highly toxic to both the soil ecosystem and human health. Causes of heavy metal contamination in soil:

- Industrial activities such as mining and manufacturing release large amounts of lead (Pb), arsenic (As), mercury(Hg), cadmium(Cd), chromium(Cr), and zinc(Zn) into the soil.
- Agricultural practices such as pesticide and fertilizer directly contaminate the soil as they introduce heavy metals into the soil. Overuse of phosphate fertilizers can also increase the level of cadmium in the soil. Irrigation with contaminated water is another major aspect to build-up of heavy metals in the soil.
- Urbanization and waste disposal, like waste disposal in landfills, often result in the leaching of heavy metals in soil. Even traffic vehicle emissions can deposit metals like lead, zinc, and copper in nearby soils, particularly around busy roads and industrial areas.
- Mining and smelting of metals is another major cause as smelting operations: Metal refining processes can release harmful metals into the surrounding environment, often leading to soil contamination in nearby areas.
- Atmospheric deposition, such as airborne contaminants: Heavy metals can be deposited onto soil through atmospheric deposition, particularly in areas near industrial emissions or smelting operations.

Effects of Heavy Metal Contamination in Soil

1. Toxicity to Soil Microorganisms

- **Soil Microbial Communities:** Heavy metals, like mercury, lead, and arsenic, are highly toxic to soil microorganisms. These organisms play a critical role in nutrient cycling, decomposition, and soil structure maintenance. Contaminants can disrupt their functions, leading to decreased soil fertility.
- **Bacterial and Fungal Growth:** High concentrations of heavy metals can inhibit microbial growth, potentially leading to reduced organic matter decomposition and nitrogen fixation.

2. Reduced Soil Fertility

- **Disruption of Soil Nutrient Balance:** Heavy metals can interfere with the availability of essential nutrients like phosphorus, potassium, and calcium, making it difficult for plants to

absorb these nutrients. This results in stunted plant growth and reduced agricultural productivity.

- **Soil pH Alteration:** Some heavy metals, such as iron and aluminum, can lower soil pH, making the soil more acidic and less suitable for plant growth.

3. Toxicity to Plants

- **Bioaccumulation in Plants:** Certain plants can take up heavy metals from the soil, leading to the accumulation of these metals in their tissues. This process, known as bioaccumulation, can harm the plant by disrupting metabolic processes, photosynthesis, and water uptake.
- **Reduced Crop Yield:** Contaminated soil affects plant growth by inhibiting seed germination, root development, and overall plant health. This leads to reduced agricultural yield and crop failure, especially for crops like rice, vegetables, and fruit trees.
- **Translocation to Edible Parts:** Heavy metals like cadmium, lead, and arsenic can be translocated to the edible parts of plants, posing health risks when consumed by humans and animals.

4. Water Contamination

- **Leaching into Groundwater:** Heavy metals in soil can leach into the groundwater, contaminating drinking water sources and posing a significant health risk to human populations relying on groundwater.
- **Surface Water Contamination:** Runoff from heavy metal-contaminated soils can lead to the contamination of nearby rivers, lakes, and streams, impacting aquatic life and potentially affecting local water supplies.

5. Ecological Damage

- **Loss of Biodiversity:** Heavy metal contamination can lead to a loss of biodiversity by reducing the availability of habitable environments for plants, animals, and microorganisms. This disrupts ecosystems and food webs. Bioaccumulation in aquatic systems: Metals like mercury and cadmium can bioaccumulate in aquatic organisms, leading to

the poisoning of fish, aquatic invertebrates, and other organisms at higher trophic levels.

6. Health Risks to Humans and Animals

- **Food Chain Contamination:** Heavy metals in soil can enter the food chain through crops, livestock, and water sources. Consuming contaminated food can lead to chronic poisoning, particularly with metals like cadmium, mercury, and lead.
- **Human Health:** Long-term exposure to heavy metals can cause various health issues:
 - **Lead:** Neurological damage, especially in children, developmental delays, and cognitive impairment.
 - **Cadmium:** Kidney damage, lung cancer, and bone disease.
 - **Arsenic:** Skin lesions, lung cancer, and cardiovascular diseases.
 - **Mercury:** Neurological and developmental problems, particularly in fetuses and young children.
 - **Animal Toxicity:** Livestock grazing on contaminated soils may accumulate heavy metals, leading to health problems like liver damage, reproductive failure, and even death.

III. METHODOLOGY

Detection of heavy metals in soil is part of practice in agriculture department of Government of India for this soil testing labs are established in every district as well as state soil testing lab. However, it cannot be denied that due to excessive technical and financial limitations, heavy metals cannot be completely removed from the soil; however, its complexity can be somewhat addressed through certain remedial techniques. For this, we can work on reducing heavy metal contamination using various culturing methods, chemical methods, and additive mineral methods. Although traditional methods used in agriculture can also help in reducing the excess of heavy metals, they also have many drawbacks. Scientists have used several innovative remediation technologies to remove heavy metals at various specific locations and to make contaminated soil effective and sustainable, including

physiochemical remediation like phytoremediation, ion exchange, nanoremediation, precipitation, encapsulation, chemical extraction, and chemical leaching.

Phytoremediation

Phytoremediation, also referred to as green remediation, botano-remediation, agro-remediation, or vegetative remediation, is an environmental clean-up method that capitalizes on plants, their associated microorganisms, soil modifications, and agricultural techniques to eradicate, confine, or neutralize harmful substances in the environment. The concept of using plants that accumulate metals to remove heavy metals and other toxins was first suggested in 1983, although this technique has actually been utilized for the past three centuries to treat wastewater discharges. Plants play a crucial role in either breaking down or decomposing organic contaminants as well as extracting and stabilizing metal pollutants.

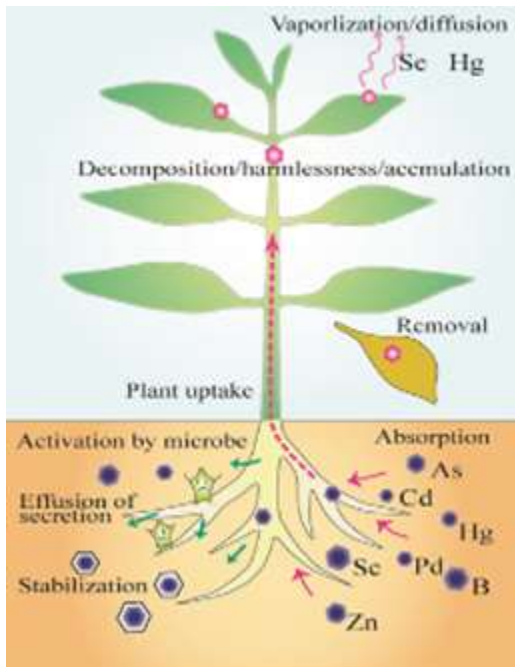


Figure 1. Phytoremediation in plants.

There are several physical and chemical methods available for the removal of heavy metal ions. Some well-known physiochemical (conventional) methods for heavy metal removal are membrane filtration, precipitation, flotation, precipitation, and physical

adsorption. A few important physiochemical methods are described in Figure 2.



Figure 2. Physiochemical methods.

IV. RESULT AND DISCUSSION

Soil remediation is needed all over the world to protect our environment and life on earth. Many government and private agencies are working together for conservation of soil. In our proposed work, we suggest some effective and less cost-consuming methods for removing heavy metals from contaminated soil. The following expected outcomes are proposed:

- Identification of heavy metals in soil in specific land/area.
- Identify the level of toxicity in soil and alert the respondent.
- Recommendations for suitable remediation method.
- Recommendations for combined approaches (e.g., phytoremediation + chemical oxidation) for reduction of heavy metals.
- Guidelines for specific metal--soil-type combinations.

REFERENCES

1. Lars Fribreg L. and Elinder C.G.: Biological monitoring of toxic metals. Scandinavian Journal

- of Work Environment & Health, 19 (1): 7--13, (1993).
2. Nicholson F.A., Smith S.R., and Alloway: An inventory of heavy metals inputs to agricultural soils in England and Wales. *Science of The Total Environment*, 311 (1–3): 205--219 (2003).
 3. Sharma R.K., Agrawal M., and Marshall F.: Heavy metal contamination of soil and vegetables in suburban areas of Varanasi, India. *Ecotoxicology and Environmental Safety*, 66 (2) 258--266 (2007).
 4. Iqbal M.A., Choudhary M.N., Zaib S., Imran M., Ali K., and Iqbal A.: Accumulation of heavy metals (Ni, Cu, Cd, Cr, Pb) in agricultural soils and spring seasonal plants, irrigated by industrial waste water. *Journal of Environmental Technology and Management*, 2 (1) (2011).
 5. Zhang X., Wang H., and Huang H.: Using biochar for remediation of soils contaminated with heavy metals and organic pollutants, contaminated land. *Ecological Assessment and Remediation Conference Series (CLEAR 2012). Environmental Science and Pollution Research*, 20, 8472--8483 (2013).
 6. Alloway B.J.: Trace metals and metalloids in soils and their bioavailability. *Heavy Metals in Soils. Book* (2013).
 7. Mathur N. and Kumar A.: Physico-chemical characterization of industrial effluents contaminated soil of Sanganeer. *Journal of Emerging Trends in Engineering and Applied Sciences*, 4 (2) (2013), <https://hdl.handle.net/10520/EJC135893>.
 8. Wuhan R.A., Okieimen F.E., and Vesuwe R.N.: Mixed contaminant interaction in soil: Implications for bioavailability, risk assessment and remediation. *African Journal of Environment Science and Technology*, 8(12), 691--706 (2014).
 9. Bhalerao S.A., Sharma A.S., and Poojari A.C.: Toxicity of nickel in plants. *International Journal of Pure and Applied Sciences*, 3 (2): 345--355 (2015).
 10. Garba H.H.: Determination of physicochemical properties of spent engine oil polluted soils sites in Bali and its Environs, Taraba State, Nigeria. *American Journal of Food Science and Technology (AJFST)*, 2(2) (2013) DOI: <https://doi.org/10.54536/ajfst.v2i2.1878>.
 11. Waris A.A., et al: Recent advances in chemical methods for remediation of heavy metals contaminated soil: a review. *Emer Life Science Research*, 4(2):45--50 (2018).
 12. Singh K., et al.: Remediation of heavy metal contaminated soils using different amendment and different species of Brassica, <http://hdl.handle.net/10603/45175> (2013).
 13. Mulugeta M. and Tibebe D.: Assessment of some selected metals from textile effluents in Amhara region using AAS and ICPOES. *International Journal of Chemistry and Materials Research*, 7 (1) 27--31 (2019).
 14. Li C., Zhou K., Qin W., Tian C., Qi M., and Tan X.: A review on heavy metals contamination in soil: effects, sources, and remediation techniques, soil and sediment contamination. *An International Journal*, 28(4), 2019, <https://doi.org/10.1080/15320383.2019.1592108>.
 15. Xiao Y., Liu S., Liang Y., and Fang J : Prospect of phytoremediation combined with other approaches for remediation of heavy metal-polluted soils. *Environmental Science and Pollution Research*, 27, 16069--16085 (2020).
 16. Haidar F.U., Coilter J.A., Cheema S.A., Farooq M., Wu J., Zhang R., Shuaijie G. and Liqun C.: Co-application of biochar and microorganisms improves soybean performance and remediate cadmium-contaminated soil. *Ecotoxicology and Environmental Safety*, 214, 112112 (2021).
 17. Jehan S., Muhammad S., Ali W., and Hussin M.L.: Potential risks assessment of heavy metal(loid)s contaminated vegetables in Pakistan: a review. *Geocarto International*, 37(24) (2022) <https://doi.org/10.1080/10106049.2021.1969449>.
 18. D'Amore J.J., Al-Abed S.R., Scheckel, K.G., and Ryan J.A.: Methods for speciation of metals in soils: a review. *Journal of Environmental Quality*, 34(5), 1707--1745 (2005).
 19. Djingova R. and Kuleff I.: Instrumental techniques for trace analysis, in *Trace Elements: Their Distribution and Effects in the Environment*, J. P. Vernet, Ed., Elsevier, London, UK, 2000.

20. Garbisu C. and Alkorta I.: Phytoextraction: a cost-effective plant-based technology for the removal of metals from the environment. *Bioresource Technology*, 77(3) 229–236 (2001).
21. Gaur A. and Adholeya A.: Prospects of arbuscularmycorrhizal fungi in phytoremediation of heavy metal contaminated soils. *Current Science*, 86(4) 528–534(2004).
22. Gupta S., Thakur R., and Sahu M.: Cadmium as a pollutant in environment and agriculture. *Journal of Industrial Pollution Control*, 23(2): 351–356 (2007).
23. Huang J.W., Chen J., Berti W.R., and Cunningham S.D.: Phytoremediation of lead-contaminated soil: role of synthetic chelates in lead phytoextraction. *Environmental Science Technology* 31, 800–805 (1997).
24. Jones L.H.P. and Jarvis S.C.: The fate of heavy metals. In *The Chemistry of Soil Processes*, D. J. Green and M. H. B. Hayes, Eds., John Wiley & Sons, New York, NY, USA, 1981, p. 593.
25. Karaca A., Cetin, S.C., Turgay O.C., Kizilkaya R.: Effects of heavy metals on soil enzyme activities. In: *Soil Heavy Metals*, I. Sherameti and A. Varma (Eds.), *Soil Biology*, Heidelberg 19, 2010, pp. 237–265.
26. Khan S., Cao Q., Zheng Y.M., Huang Y.Z., and Zhu Y.G.: Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China, *Environmental Pollution*, 152(3) 686–692 (2008).
27. Kibra M.G.: Effects of mercury on some growth parameters of rice (*Oryza sativa* L.). *Soil & Environment*, 27(1), 23–28 (2008).
28. Kurek E. and Bollag J.M.: Microbial immobilization of cadmium released from CdO in the soil. *Biogeochemistry*, 69(2):227–239 (2004).
29. Liu D., Jiang W., Liu C., Xin C., and Hou W.: Uptake and accumulation of lead by roots, hypocotyls and shoots of Indian mustard [*Brassica juncea* (L.)]. *Bioresource Technology*, 71(3), 273–277 (2000).
30. Mattigod S.V. and Page A.L.: Assessment of metal pollution in soil, In *Applied Environmental Geochemistry*, Academic Press, London, UK, 1983, pp. 355–394.
31. Moral R., Gomez I., Pedreno J.N., and Mataix J.: Absorption of Cr and effects on micronutrient content in tomato plant (*M. lycopersicumesculentum*), *Agrochimica*, vol. 40(2–3), 132–138 (1996).
32. Rattan R.K., Datta S.P., Chandra S., and Saharan N.: Heavy metals and environmental quality – Indian scenario. *Fertilizer News* 47(11) 21–26 & 29–40 (2002).
33. Roy S., Labelle S., and Mehta P.: Phytoremediation of heavy metal and PAH contaminated brown field sites. *Plant and Soil*, 272(1–2) 277–290(2005).
34. Schmidt U.: Enhancing phytoextraction: the effect of chemical soil manipulation on mobility, plant accumulation and leaching of heavy metals. *Journal of Environmental Quality* 32(6) 1939–1954 (2003).
35. Sheppard, S. C.: Summary of phytotoxic levels of soil arsenic. *Water Air Soil Pollution* 64, 539–550 (1992).
36. USEPA – US Environmental Protection Agency (2000) Introduction to Phytoremediation, National Risk Management Research Laboratory, EPA/600/R-99/107, <http://www.clu-in.org/download/remed/introphyto.pdf>.
37. USEPA (1994). A plain English guide to the EPA part 503 biosolids rule. USEPA Rep. 832/R-93/003, USEPA, Washington, DC, USA.
38. USEPA. Report: Recent developments for in situ treatment of metals contaminated Soils, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, 1996.
39. Wang Y.P., Shi J.Y., Wang H., Li, Q., Chen X.C., and Chen Y.X.: The influence of soil heavy metals pollution on soil microbial biomass, enzyme activity, and community composition near a copper smelters. *Ecotoxicology and Environmental Safety* 67, 75–81(2007b).