



AMERICAN JOURNAL OF ENVIRONMENTAL ECONOMICS (AJEE)

ISSN: 2833-7905 (Online)

VOLUME 3 ISSUE 1 (2024)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

An Academic Review on Heavy Metals in the Environment: Effects on Soil, Plants Human Health, and Possible Solutions

Paul Obokparo Ewubare^{1*}, Sarah Onosteike Aliyu¹, Ikioukenigha Michael², Joy Osebhajimede Ejakhaegbe¹, Justice Obomejero³
Sunday Osarodion Okoro⁴, Oluwaseyi Joseph Olukayode¹

Article Information

Received: July 03, 2024

Accepted: August 06, 2024

Published: August 10, 2024

Keywords

*Heavy Metals, Bioaccumulation,
Environmental Contamination,
Human Health, Phytoremediation,
Microbial Remediation*

ABSTRACT

Heavy metal uptake by plants and successive accumulation in human tissues and biomagnification through the food chain cause significant concerns for both human health and the environment. Human activities, including industrial, agricultural, traffic, domestic, and mining processes, have increased the toxic levels of these metals beyond those contributed by natural rock-forming processes. Heavy metals are potentially toxic to plants, resulting in chlorosis, weak growth, yield depression, reduced nutrient uptake, metabolic disorders, and diminished nitrogen-fixation ability. Utilization of food crops contaminated with heavy metals is a major food chain route for human exposure. The cultivation of plants in contaminated soil poses a potential risk since vegetal tissues can accumulate heavy metals. Owing to their toxicity and potential for bioaccumulation, these compounds should be subject to mandatory monitoring, particularly in soil and plants, to prevent their entry into the human food system. Furthermore, studies have shown that phytoremediation and microbial remediation are promising techniques for mitigating the negative effects of heavy metals contamination. These methods are environmentally friendly and economically effective, making them applicable globally. This review paper summarizes the effects of heavy metals in our environment by examining relevant works related to the topic. To achieve this, databases such as Google Scholar, Frontier in Microbiology, African Journals Online (AJOL), Scopus, Web of Science, ScienceDirect, and Directory of Open Access Journals (DOAJ) were explored to identify studies on the effects on soil, plants, human health and managing heavy metals in the environment.

INTRODUCTION

Heavy metals are serious environmental pollutants, with their toxicity becoming increasingly significant for ecological, evolutionary, nutritional, and environmental reasons (Jaishankar *et al.*, 2013; Nagajyoti *et al.*, 2010). Metals are naturally present in the earth's crust, and their levels in the environment can vary widely across different regions, leading to spatial variations in background concentrations. The distribution of metals in the environment is influenced by the properties of the metals themselves and various environmental factors (Khlifi and Hamza-Chaffai, 2010). Heavy metals enter the environment through both natural and human activities. Sources include natural weathering of the earth's crust, mining, soil erosion, industrial discharge, urban runoff, sewage effluents, pesticides and disease control agents used on plants, and air pollution fallout, among others (Ming-Ho, 2005). While some individuals are primarily exposed to these contaminants in the workplace, most people encounter these toxic elements through their diet (food and water). The contamination cycle of heavy metals typically follows this path: industry, atmosphere, soil, water, food, and humans. Although the toxicity and resulting threat to human health depend on the concentration of the contaminant, it is well-known that

chronic exposure to low levels of heavy metals and metalloids can have harmful effects (Castro and Méndez, 2008).

Heavy metals taken up by plants can accumulate in human tissues and biomagnify through the food chain, posing concerns for both human health and the environment (Wong and Selvam, 2006). These metals exert toxic effects on soil microorganisms, leading to changes in the diversity, population size, and overall activity of soil microbial communities (Ashraf and Ali, 2007). High levels of lead (Pb) in soils can decrease soil productivity, and even low concentrations of Pb can inhibit crucial plant processes such as photosynthesis, mitosis, and water absorption. Symptoms of toxicity in plants include dark green leaves, wilting of older leaves, stunted foliage, and brown short roots (Bhattacharya *et al.*, 2008). The uptake of heavy metals from soils at high concentrations poses a significant health risk through the food chain (Jordao *et al.*, 2006). Consumption of food contaminated with heavy metals can severely deplete essential nutrients in the body, leading to decreased immune defenses, intrauterine growth retardation, malnutrition-related disabilities, and higher rates of upper gastrointestinal cancer (Khan *et al.*, 2008). This academic review paper aims to assess heavy metal contamination in our environment, focusing on its

¹ University of Benin, Edo State, Nigeria

² Igbinedion University, Okada, Edo State, Nigeria

³ Imo State University, Imo State, Nigeria

⁴ Auch Polytechnic, Edo State, Nigeria

* Corresponding author's e-mail: paulewubare9@gmail.com

effects on soil, plants, and human health, and to propose possible solutions for managing these pollutants.

METHODOLOGY

The methodology for this study involved sourcing data primarily from previous research and secondary sources such as published studies, articles, and relevant materials. Databases including Google Scholar, Frontier in Microbiology, African Journals Online (AJOL), Scopus, Web of Science, ScienceDirect, and Directory of Open Access Journals (DOAJ) were systematically searched using keywords such as “heavy metals in the environment,” “heavy metal and human health,” “heavy metal and soil,” and “heavy metal and plants.” Sources were selected based on their relevance, recency, and the credibility of the publication. By synthesizing insights from scholarly articles and reports, this research aims to address issues related to heavy metals and explore potential management strategies.

DISCUSSION

Heavy metals naturally occur in the environment and are vital for survival, but they may become hazardous when they accumulate in organisms. A few of the most frequent heavy metals that contaminate the environment include mercury, cadmium, arsenic, chromium, nickel, copper, and lead (Hazrat *et al.*, 2019). Heavy metals in the environment can be absorbed by soil, which then contaminates plants growing in that soil. These plants, when consumed by humans, transfer the heavy metals, potentially leading to health issues.

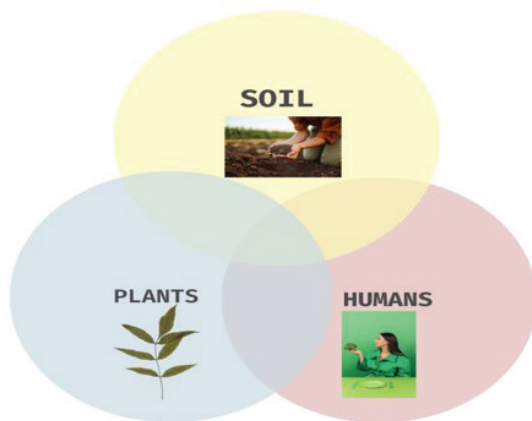


Figure 1: Interconnections of Soil, Plants, and Humans
Source: Author's Creation

In a study by Omokaro *et al.* (2023), the concentration of copper in Okra (*Abelmoschus esculentus*) cultivated on dumpsite soils in Benin City, Nigeria was investigated. The highest uptake of copper (36.0 mg/kg) was observed in residential land, while the lowest uptake (23.3 mg/kg) was recorded in farmland. However, the World Health Organization (WHO, 1996) sets a permissible limit of 10 mg/kg for copper in vegetables, suggesting that the copper content in Okra grown in dumpsite soils may

be considered high. Furthermore, the interconnected cycle above highlights the importance of monitoring and managing soil quality to prevent the accumulation of harmful substances in the food chain. Explicitly, the Soil acts as a reservoir for heavy metals, influencing their availability and uptake by plants, while the Plants absorb heavy metals from the soil, which can accumulate in edible parts. On the other hand, Humans consume plants containing heavy metals, leading to potential health risks. The Venn diagram visually emphasizes the overlap and interaction between these three components in the context of environmental contamination.

Heavy Metals

Heavy metals are a unique group of metals characterized by their high densities, atomic numbers, and atomic weights on the periodic table (Pourret *et al.*, 2021). These metals, including mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As), are particularly concerning due to their toxicity, even at low concentrations (Di *et al.*, 2023). Heavy metals typically have a specific gravity of 5 g/cm³ or higher (Sparks *et al.*, 2003) and are non-biodegradable, meaning they can persist in the environment for decades. Human activities such as industrial processes, agriculture, traffic, domestic activities, and mining have significantly increased the levels of these toxic metals in the environment compared to natural sources like rock weathering (Pam *et al.*, 2013). Metals like Pb, Cd, Hg, Cr, and As are widespread in the environment, and they are non-essential elements with no beneficial effects on humans. They are considered the most toxic to humans and animals due to their harmful health effects, even at low concentrations (Draghici *et al.*, 2010). On the other hand, metals like iron (Fe), zinc (Zn), nickel (Ni), manganese (Mn), and copper (Cu) are essential for plant growth and development at lower concentrations, playing crucial roles in physiological and biochemical functions, such as participating in redox reactions and enzymatic activities (Nagajyoti *et al.*, 2010; Vieira *et al.*, 2011). In the natural environment, heavy metals exist in various chemical forms and exhibit different behaviors regarding chemical interactions, mobility, biological availability, and potential toxicity (Osu *et al.*, 2014).

Cadmium, Mercury, and Lead

Cadmium (Cd) is released into the atmosphere through both natural processes and human activities. It can enter the aquatic environment via absorption, industrial waste, and surface runoff into soils and sediments. Humans and animals can be exposed to cadmium by ingesting contaminated food, breathing polluted air, or drinking contaminated water. Cadmium does not support plant growth or metabolic processes (Hayat *et al.*, 2018). Mercury (Hg) is another highly toxic heavy metal found in the biosphere. Human activities have increased its presence in the atmosphere, where it can transform into highly toxic methylmercury upon contact with aquatic sediments (Gworek *et al.*, 2020). Methylmercury can

enter the human body through the consumption of contaminated fish, seafood, and wildlife, leading to various neurological problems (Rice *et al.*, 2014). More so, Lead (Pb) is a non-biodegradable metal naturally present in low amounts, but its levels are continuously increasing due to human activities like manufacturing, mining, and fossil fuel burning. Lead exposure is particularly dangerous to children, as they are more susceptible to lead poisoning, especially from environmental dust laden with lead (Loh *et al.*, 2016).

Manganese, Chromium, and Cobalt

Manganese (Mn) is abundant in nature and can be released into the air during the combustion of methylcyclopentadienyl manganese tricarbonyl (MMT), a gasoline additive. While essential for various physiological activities, excessive manganese can be toxic (Loranger and Zayed, 1995; O’Neal and Zheng, 2015). Chromium (Cr) exists in two stable oxidation states in the environment: chromium (III) and chromium (VI). Chromium (III) is less hazardous than chromium (VI), which can convert to the less toxic form during industrial processes. However, chromium (VI) remains highly toxic and carcinogenic, posing significant risks in areas with high industrial emissions (Coetzee *et al.*, 2020; Kimbrough *et al.*, 1999). Cobalt (Co) is widely distributed in the environment and used in alloy production. While small amounts of cobalt are typically harmless, large discharges into the environment can be fatal (Domingo, 1989).

Nickel, Copper, and Zinc

Nickel (Ni) is naturally abundant and extensively used in industry. It is released from both natural and anthropogenic sources into the atmosphere and can cause allergies, nasal and lung cancer, and kidney and cardiovascular diseases due to inhalation of contaminated air (Genchi *et al.*, 2020; Lu *et al.*, 2005). Copper (Cu) is an essential micronutrient for living organisms, playing a crucial role in the normal physiological functions of plants, such as chlorophyll formation, photosynthesis, and carbohydrate and protein metabolism. A lack of copper can disrupt these important metabolic processes, while excessive exposure can lead to

toxicity (Schwartz *et al.*, 2003). Zinc (Zn) is a fundamental and widespread metal, involved in numerous enzymatic reactions by acting as a cofactor. The toxicity of zinc depends on the manner and quantity of exposure. Major sources of zinc in the environment include smelting and mining. Significant amounts of zinc are released into the environment through mineral processing activities, which can impact ecosystems and living organisms (Zhang *et al.*, 2012).

Antimony and Thallium

Antimony is a toxic element present in nanogram amounts in the air. Its emissions into the atmosphere can result from natural events such as volcanic activity and weathering, as well as human activities (He *et al.*, 2019). Thallium is found in the environment in various forms and is highly toxic to biological organisms. Its toxicity surpasses that of other heavy metals. Monovalent thallium ions appear in natural water and can be released into the air through aqueous routes (Peter & Viraraghavan, 2005). Additionally, industrial emissions significantly contribute to increased thallium levels in the atmosphere. Exposure to thallium poses severe health risks to humans (Kazantzis, 2000).

Sources of Heavy Metals into the Soil

Heavy metals are released into the environment from various sources including mining, urbanization, chemical industry, sewage plants, pesticide plants, biomedical and unsafe agricultural practices as described in Figure 2 below. The United Nations Environment Program (UNEP/GPA) and the Global Plan of Action (GPA) recognize electronic waste (e-waste) which includes devices like mobile phones, tablets, computers, and smartwatches as a major threat to the environment and human well-being. This is primarily due to the presence of heavy metals like Hg, Cd, and Pb in electronic devices, which can pose serious risks to both the environment and human health if not properly disposed of according to UNEP/GPA (2006) and Tchounwou *et al.* (2012). More so, major unrestricted and monitored dumpsites are also major source of heavy metal into soils and underground water.

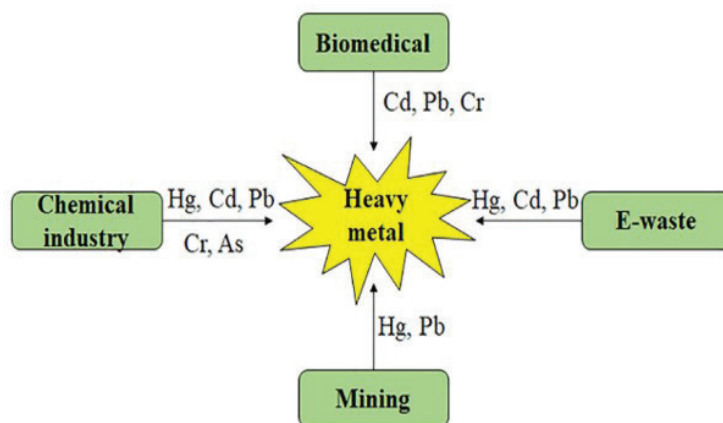


Figure 2: A schematic diagram illustrating the origins of heavy metal pollution
 Source: Das *et al.* (2023)

The pollution levels of these heavy metals into the environment are influenced by industrial activities, geographic locations, regulatory oversight, and diverse sources. For instance, Hg primarily emanates from coal combustion, electric/light bulb, wood preservatives, leather tanning, ointments, thermometers, adhesives and paints (Bradl, 2005; Mukherjee *et al.*, 2008), in most areas in Africa there are industrial activities with no regulatory activities or policies governing their activities in most areas. Cd often originates from industries like battery manufacturing, paint pigments, pesticides, galvanized pipes, plastics, polyvinyl and copper refineries. Pb, an extremely toxic metal, commonly originates from substances like Pb-based paints, gasoline and mobile batteries. Cr is emitted from a variety of industrial activities, including petroleum refining, electroplating, leather tanning, textile manufacturing, and pulp processing. As, a naturally occurring element in the Earth's crust, is released into the environment through a variety of human activities, including mining, agricultural practices, automobile exhaust and industrial dust, wood preservatives, and dyes (Choppala 2013; Velusamy *et al.*, 2021; Rees and Fuller, 2020; Jiang *et al.*, 2023). Human activities through industrial, agricultural, traffic, domestic, mining and other human activities processes have contributed to increase the toxic levels of these metals when compared to those contributed from rock forming processes (Pam *et al.*, 2013).

Sources of Heavy Metals in Soil

Soil is essential for supporting terrestrial ecosystems and biodiversity. However, heavy metals are prevalent pollutants in the soil environment and can negatively impact microorganisms, plants, and animals. The European Environment Agency (EEA) has set limit values for soil pollutant levels of various heavy metals, including Hg (0.20 ppm), Cd (0.44 ppm), Pb (0.48 ppm), Cr (0.20 ppm), and As (0.11 ppm) (European Union, 2002; Baritz *et al.*, 2023). Heavy metals can accumulate in soils to toxic levels due to the long-term application of untreated liquid and solid waste, industrial activities, and fertilizers (Papafilippaki *et al.*, 2008). When soils are irrigated with these wastes, heavy metals can accumulate on the surface. As the soil's capacity to retain heavy metals diminishes with repeated waste application, these metals can leach into groundwater or remain available for plant uptake. Wastewaters often contain significant concentrations of organic and inorganic nutrients, including nitrogen, phosphate, micronutrients, and heavy metals (Alshammary & Qian, 2008; Mojiri & Amirossadat, 2011). Urban and industrial effluents are major sources of heavy metals in wastewater, which can build up to toxic levels in soils with long-term use (Tabari *et al.*, 2008). Given that wastewater is an uncommon water source, its application in agriculture needs careful management to maximize benefits and prevent environmental and health risks (Asgari *et al.*, 2007).

Contamination of soils by heavy metals like Cd, Ni, Zn, Pb, and Cu has increased dramatically over the past few decades due to activities such as mining, smelting, manufacturing, the use of agricultural fertilizers and pesticides, municipal waste, traffic emissions, and industrial effluents (Morgan, 2013; Chibuike and Obiora, 2014). This contamination is now widespread (Al-Nagger *et al.*, 2013), causing significant land degradation and adversely affecting the environment and ecosystems worldwide (Li *et al.*, 2013). Heavy metals in wastewater-irrigated soils can contaminate food, posing hazards to humans and animals (Jolly *et al.*, 2013). These metals are poorly soluble in water and cannot be degraded, leading to accumulation in soils and plants (Ghoneim *et al.*, 2014). They persist in soil, leaching into groundwater and potentially inducing enhanced antioxidant enzymatic activities in plants or becoming adsorbed onto solid soil particles (Iannelli *et al.*, 2002).

Mechanism of Heavy Metals in Soil

Heavy metal pollution in soil not only affects plant quality and yield but also changes the size, composition, and activity of microbial communities (Yao *et al.*, 2003). Heavy metals are a major source of soil pollution, adversely affecting soil biological and biochemical properties. Soil characteristics like organic matter, clay content, and pH significantly influence the impact of metals on these properties (Speira *et al.*, 1999). Heavy metals indirectly affect soil enzymatic activities by altering microbial communities that synthesize enzymes (Shun-hong *et al.*, 2009). They exhibit toxic effects on soil biota, affecting key microbial processes and reducing the number and activity of soil microorganisms. However, long-term exposure can increase the tolerance of bacterial communities and fungi like arbuscular mycorrhizal (AM) fungi, which play a crucial role in restoring contaminated ecosystems (Mora *et al.*, 2005).

Heavy metals cause a decrease in bacterial species richness and an increase in soil actinomycetes or a decrease in both the biomass and diversity of bacterial communities (Chen *et al.*, 2010). Different metals influence enzyme activities in various ways due to their different chemical affinities in the soil system. For example, Cd is more toxic to enzymes than Pb because of its greater mobility and lower affinity for soil colloids, and Cu inhibits β -glucosidase activity more than cellulose activity (Karaca *et al.*, 2010). Soil pH significantly affects the solubility or retention of metals in soils, with heavy metals exhibiting toxic effects on soil biota by affecting key microbial processes and reducing the number and activity of soil microorganisms (Ghosh and Singh, 2005). Heavy metals have low environmental mobility, making a single contamination event potentially lead to long-term exposure to humans, microbes, fauna, flora, and other soil communities (Adeleken and Abegunde, 2011). Farming on dumpsites can negatively impact human health due to high concentrations of trace metals in plants, which subsequently enter the food chain (Elaigwu *et al.*, 2007).

Heavy Metals and Plants

The absorption of heavy metals by plant roots is a primary route for these contaminants to enter the food chain (Jordao *et al.*, 2006). The uptake and accumulation of heavy metals by plants can pose significant threats to animal and human health (Sprynskyy *et al.*, 2007). Some heavy metals, such as arsenic (As), cadmium (Cd), mercury (Hg), lead (Pb), and selenium (Se), are not essential for plant growth and do not serve any known physiological functions. Others, like cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn), are essential elements required for normal plant growth and metabolism. However, these elements can become toxic when their concentrations exceed optimal levels (Rascio and Izzo, 2011). Heavy metals can cause chlorosis, weak plant growth, yield depression, and reduced nutrient uptake, leading to metabolic disorders and decreased nitrogen fixation in leguminous plants (Guala *et al.*, 2010). The accumulation of heavy metals in plants depends on various soil factors, including pH, electrical conductivity (EC), clay content, organic matter content, and physical and mechanical soil characteristics. Plants absorb heavy metals through mechanisms such as absorption, ionic exchange, and redox reactions (Zabalawy *et al.*, 2015). The efficiency of different plants in absorbing metals is evaluated by plant uptake or soil-to-plant transfer factors (Khan *et al.*, 2008). Elevated levels of lead (Pb) in soils can reduce soil productivity and inhibit vital plant processes, such as photosynthesis, mitosis, and water absorption, leading to symptoms like dark green leaves, wilting of older leaves, stunted foliage, and short brown roots (Bhattacharya *et al.*, 2008). The presence of increasing concentrations of lead (Pb) can delay seed germination, possibly due to mechanisms like leaching, chelation, metal binding, or accumulation by microorganisms that neutralize the toxic effects of lead (Ashraf and Ali, 2007).

Heavy Metals and Human Health

High concentrations of heavy metals in plants can pose significant health risks when these plants are consumed, considering the implications for the food chain. According to the World Health Organization (WHO) guidelines, acceptable levels of heavy metal pollutants in drinking water are: Hg—0.001 ppm, Cd—0.005 ppm, Pb—0.05 ppm, Cr—0.05 ppm, and As—0.05 ppm (WHO, 2004). The Food and Agriculture Organization (FAO) of the United Nations and WHO set maximum limits for heavy metal consumption through vegetables: Hg—0.05 mg/kg for all vegetables; Cd—0.2 mg/kg for leafy vegetables, 0.3 mg/kg for root vegetables, and 0.1 mg/kg for other vegetables; Pb—0.15 mg/kg for all vegetables; Cr—0.1 mg/kg for all vegetables; and As—0.1 mg/kg for all vegetables (Wu, 2014; Kesson *et al.*, 2015). The consumption of food crops contaminated with heavy metals represents a significant risk, as these metals can accumulate in plant tissues and subsequently enter the food chain (Jordao *et al.*, 2006). Heavy metals

become toxic when they are not metabolized by the body and accumulate in soft tissues (Sobha *et al.*, 2007). Chronic ingestion of toxic metals can have severe health impacts, often becoming apparent only after many years of exposure (Khan *et al.*, 2008). Specific heavy metals are hazardous to human health. For instance, cadmium (Cd) is a well-known toxicant with a specific gravity 8.65 times greater than water. Target organs for Cd toxicity include the liver, placenta, kidneys, lungs, brain, and bones (Sobha *et al.*, 2007). Cd is emitted into the air by mines, metal smelters, and industries using cadmium compounds for alloys, batteries, pigments, and plastics, despite stringent controls in many countries (Harrison, 2001). Symptoms of Cd exposure include nausea, vomiting, abdominal cramps, dyspnea, and muscular weakness, with severe exposure leading to pulmonary edema and death. Chronic inhalation of Cd can cause pulmonary and renal effects (Duruibe *et al.*, 2007).

Zinc (Zn) is relatively non-toxic, especially when taken orally, but excessive amounts can cause system dysfunctions affecting growth and reproduction. Clinical signs of zinc toxicity include vomiting, diarrhea, bloody urine, icterus (yellow mucus membrane), liver failure, kidney failure, and anemia (Lalor, 2008). Copper (Cu), an essential element in mammalian nutrition, can be toxic at high levels, causing mucosal irritation, capillary damage, hepatic and renal damage, and central nervous system irritation (Stern *et al.*, 2007). Nickel (Ni) exposure can cause skin irritation and damage to the lungs, nervous system, and mucous membranes (Argun *et al.*, 2007). On the other hand, Lead (Pb) is physiologically and neurologically toxic to humans, with acute poisoning causing dysfunction in the kidneys, reproductive system, liver, and brain, potentially leading to sickness and death (Odum, 2000). Pb exposure occurs primarily through contaminated food, air, and drinking water (Ming-Ho, 2005). Mercury (Hg), which has no known function in human biochemistry, is highly toxic and can cause spontaneous abortion, congenital malformations, gastrointestinal disorders, and severe neurological disorders (Duruibe *et al.*, 2007). Hg exposure can occur through agriculture, pharmaceuticals, industrial processes, and contaminated air, water, and soil (Zhang and Wong, 2007). High levels of Hg exposure can cause permanent damage to the brain, kidneys, and developing fetus (ATSDR, 2003). Heavy metals like Hg and Cd can induce DNA damage, cause chromosome aberrations, and alter DNA replication and transcription, leading to serious health issues such as Alzheimer's disease, lung damage, and skin ailments (Shekhawat & Meshram, 2020; Harischandra *et al.*, 2021; Coetzee *et al.*, 2020; Kothapalli, 2021; Das *et al.*, 2023).

Heavy Metal Concentration in Vegetables

Certain edible crops can accumulate heavy metals, even in minimal amounts. These heavy metals can enter the food chain, disrupt the food pyramid, and pose significant health risks, including cancer and liver diseases. Vegetables such as brinjal, gourd, spinach, coriander, tomato, and

pumpkin are particularly susceptible to heavy metal uptake by their roots, which can then be transported to the edible parts of the plant (Gupta *et al.*, 2022; Minhas *et al.*, 2022). Consequently, consuming vegetables containing heavy metals can be extremely hazardous to human health. Research by Alexander *et al.* (2006) involving vegetables grown in soil contaminated with heavy metals showed significant variations in metal accumulation levels among different vegetables. For cadmium (Cd), lettuce exhibited higher accumulation (8.6 mg/kg dry matter) compared to spinach (5.8 mg/kg dry matter), onion (3.6 mg/kg dry matter), carrot (2.0 mg/kg dry matter), pea (0.29 mg/kg dry matter), and French bean (0.07 mg/kg dry matter). Lettuce also recorded the highest concentration of lead (Pb), nearly double that of onions, which had the second-highest average value. The sequence was as follows: lettuce (14.6 mg/kg dry matter) > onion (7.5 mg/kg dry matter) > carrot (5.8 mg/kg dry matter) > spinach (1.8 mg/kg dry matter) > pea (0.78 mg/kg dry matter) > French bean (0.34 mg/kg dry matter).

A study by Zhu *et al.* (2021) revealed that the concentration of heavy metals in the edible parts of vegetables varied, with leafy vegetables having the highest amounts, followed by stalk vegetables, root vegetables, solanaceous vegetables, legume vegetables, and melon vegetables. Previous reports have suggested that edible crops grown in industrial areas such as coal mines and petrochemical plants tend to contain higher levels of heavy metals (Haque *et al.*, 2021). Human exposure to heavy metals primarily occurs through the consumption of edible crops, accounting for 90% of the exposure, with the remaining 10% attributed to the inhalation of polluted air particles (Khan *et al.*, 2015). Excessive levels of heavy metals can harm various organs such as the brain, muscles, nerves, liver, kidneys, and heart. The European Protection Agency (EPA) has reported that prolonged exposure to heavy metals can result in severe cancer. Research by the WHO indicates that higher exposure to

heavy metals puts 10% of women at risk of infertility (Abudawood *et al.*, 2021; Bhardwaj *et al.*, 2021).

Managing Heavy Metal Contamination in the Environment

Several techniques are used to decontaminate the environment from heavy metals and prevent their entry into the food chain, but these methods tend to be costly and have suboptimal efficacy (Li *et al.*, 2019; Qasem *et al.*, 2021). For example, Omokaro (2024), who worked on Farmers' Perceptions of Pest and Disease Control Methods in South-South Nigeria suggested that Integrated Pest Management is an environmentally friendly approach that combines biological, cultural, and chemical methods to manage pests. The author further noted that the significant use of chemical pesticides indicates a reliance on chemical control, which can have environmental and health implications if not managed properly. The increasing concerns about environmental contamination have driven the development of technologies to assess the presence and mobility of metals in soil, water, and wastewater. Both private and government institutions face technical challenges in removing contaminants from the environment. Phytoremediation has emerged as a popular and economical plant-based technology for effectively addressing environmental issues. This process uses plants to extract and remove elemental pollutants or reduce their bioavailability in soil or water (Li and Tran, 2023). Phytoremediation is widely accepted due to its eco-friendliness, affordability, and high effectiveness. It takes advantage of the unique and selective uptake capabilities of plant root systems, along with the translocation, bioaccumulation, and contaminant degradation abilities of the entire plant body. Both aquatic and terrestrial plant species have been utilized to eliminate pollutants from the environment (Sharma, 2021; Nedjimi, 2021; Huang *et al.*, 2021).

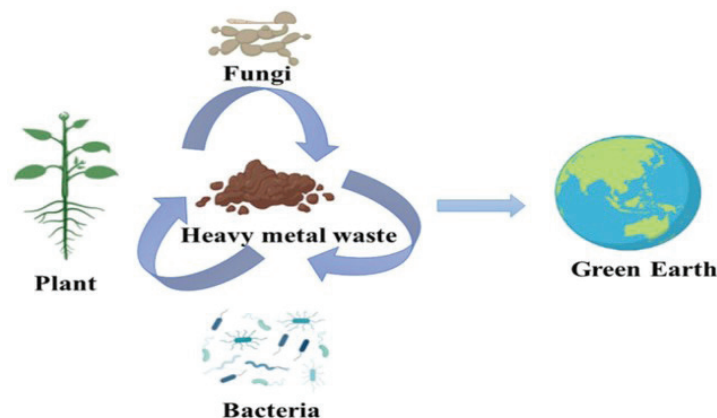


Figure 2: An illustrative diagram elucidating bioremediation, highlighting the crucial roles of plants, bacteria, and fungi
Source: Das et al. (2023)

Phytoremediation Process

Phytoremediation encompasses several processes, including phytoextraction, phytoaccumulation, phytovolatilization,

phytostabilization, and phytotransformation (Liu and Tran, 2021). Phytoextraction is a technique that involves the absorption of organic and inorganic pollutants

through the roots and stems. Besides, some particular plant species, like *Brassica juncea*, *Cassia alata*, *Celosia argentea*, *Kummerowia striata*, *Helianthus annuus*, *Momordica charantia*, *Nicotiana tabacum*, *Salix mucronata*, *Salix viminalis*, *Solanum lycopersicum*, *Solanum melongena*, *Swietenia macrophylla*, *Pteris vittata*, and *Vigna unguiculata*, have the potential to be used as suitable plant selections to enhance the phytoextraction process (Hazarika *et al.*, 2022; Kumar *et al.*, 2022). In phytostabilization, in this process, plants accumulate and immobilize heavy metals by binding with biomolecules. *Miscanthus giganteus*, *Avena sativa*, and *Sinapis alba* can also help to stabilize heavy metal compounds in the soil (Muthusamy *et al.*, 2022; Hegedus *et al.*, 2023). There are several processes by which plants can reduce contaminants which are further explained below.

Phytoextraction and Rhizofiltration

Phytoextraction, also called phytoaccumulation, involves the accumulation of heavy metals from earth land. In this method, the uptake and translocation of contaminants by plants root into the aerial portions of plants and deposited into vacuoles. The mechanism during the accumulation process is used to absorb and precipitate the toxic metals by metal-phytochelatin complex before translocating into the shoot, leaf and stem parts of the plant. The hyperaccumulator species accumulate a higher concentration of heavy metals (Asgari *et al.*, 2019; Gul *et al.*, 2021). More so, Rhizofiltration involves the elimination of heavy metals using plant roots. Though it is comparable to phytoextraction, in this process, plants remove contaminants from wastewater or groundwater rather than soil. In this process, plant roots assimilate or adsorb pollutants from wastewater, groundwater, or surface water. Generally, aquatic plant species are employed to eliminate pollutants through rhizofiltration. Rhizofiltration is effective for removing Cd, Pb, and Cr, which are primarily accumulated in the roots. Sunflower, tobacco, and spinach exhibit promising potential in removing Pb from water (Mohan *et al.*, 2021).

Phytostabilization and Phytovolatilization

Plant roots can limit the movement of heavy metals by phytostabilization, a process that reduces toxic effects. This process involves the capture of contaminants on the root surface using transport proteins or secondary metabolites. Furthermore, the process involves the breakdown of complex organic molecules into simpler ones by coupling them with protein, amino acid, and sugar derivatives. Black nightshade, sunflower, and cowpea are among the plant species that employ phytostabilization mechanisms (Li *et al.*, 2020). However, the Phytovolatilization process entails the uptake of contaminants by plants from the soil and their conversion into less toxic volatile compounds that are released into the atmosphere. The volatile compounds are primarily released from aerial plant parts such as stems and leaves. This mechanism is effective when the contaminants are less toxic (Pouresmaieli *et al.*, 2022).

Phytodegradation (Phyto-transformation)

Phytotransformation, also known as this process, refers to the absorption of contaminants by plants, which are then metabolized or broken down into less toxic compounds and translocated to various plant organs. The organic compounds are then degraded into non-toxic forms inside the plant tissue (Nebeská *et al.*, 2021).

Microbial Remediation Process

Microbial remediation is the process of using living microorganisms such as bacteria, fungi, and archaea to break down and detoxify various chemical and metallic hazardous wastes from the environment (Yaashikaa *et al.*, 2022). Bioremediation involves the direct application of microorganisms to the polluted site in order to facilitate the degradation of contaminants. Microorganisms are used in a variety of remediation techniques, including bioaugmentation and biostimulation. In bioaugmentation, specific microorganisms are added to a contaminated site to enhance the breakdown of contaminants. In biostimulation, the environmental conditions at the site are modified to promote the growth and activity of naturally occurring microorganisms that can degrade contaminants. Physical and chemical treatments are conventional remediation methods that have drawbacks such as high cost, heavy machinery, logistical glitches, and potential environmental toxicity (Iwamoto & Nasu, 2001). In contrast, bioremediation technologies have seen significant growth and development, making it a promising method for treating soil and water contamination. Among these methods, bioremediation of oil spills is the most lucrative and environment-friendly technique (Pete *et al.*, 2021). Ewubare *et al.* (2023) posited that a reliable alternative to the use of chemical fertilizers which also increase heavy metals in agricultural produce is microbial inoculants, which can act as biofertilizers, bioherbicides, biopesticides, and biocontrol agents. Microorganisms can promote plant growth, and controlling pests, diseases, and weeds. Microbial inoculants are beneficial microorganisms applied either to the soil or the plant to improve productivity and crop health. These natural-based products are widely used to control pests and enhance soil and crop quality, thereby benefiting human health. Microbial inoculants consist of a blend of microorganisms that work with the soil and its inhabitants to improve soil fertility and health, ultimately benefiting human health. They can minimize the negative impact of chemical inputs, thereby increasing the quantity and quality of farm produce.

Furthermore, fungi are used for the remediation of pollutants in myco-remediation, a type of bioremediation. Fungi play a vital role in cleaning up contaminated sites in both soil and aquatic ecosystems (Kumar & Dwivedi, 2021). These microorganisms, which are widely present in nature, can thrive in a diverse range of environmental conditions. These microorganisms survive in extreme conditions and produce some extracellular ligninolytic enzymes like peroxidase and laccases. These enzymes

help fungi to transform pollutants into non-toxic forms. Pollutants can be adsorbed by extracellular enzymes (Shourie & Vijayalakshmi, 2022). Diverse fungal species such as *Aspergillus* sp., *Bjerkandera adusta*, *Coriolus versicolor*, *Cryptococcus* sp., *Hirschioporus laricinus*, *Inonotus hispidus*, *Mucor* sp., *Penicillium* sp., *Phanerochaete chrysosporium*, *Phlebia tremellosa*, *Phanerochaete chrysosporium*, *Pleurotus* sp., and *Trametes versicolor*, have been reported for bioremediation (Jebapriya & Gnanadoss, 2013; Singh *et al.*, 2013). Microalgae are photosynthetic microorganisms that play a vital role in the bioremediation of various types of wastewaters. According to Omokaro and Nafula (2023), microalgae are effective in the removal of nitrogen (N), phosphorus (P), and carbon (C), as well as in reducing biological oxygen demand (BOD) and removing heavy metals. These microorganisms have shown promise in producing biofuels, bioethanol, bioremediation agents, biofertilizers for agricultural production, and essential molecules like proteins. The integration of microalgae into wastewater treatment processes can significantly reduce the cost of wastewater treatment, lower the energy consumption footprint, and provide environmental sustainability compared to conventional wastewater treatment processes. This integration enhances the overall efficiency of wastewater treatment by leveraging the natural capabilities of microalgae to absorb and metabolize pollutants.

CONCLUSION

Metals occur naturally in the Earth's crust, and their concentrations in the environment can vary between different regions, resulting in spatial variations of background levels. Heavy metal accumulation in soil causes pollution, while in plants, it can lead to slow growth and even death. In humans, it can result in severe health hazards. Several toxicity evaluations have indicated that heavy metals pose a substantial threat to non-targeted living entities. These metals are taken up by plants from the soil, reducing crop productivity by inhibiting physiological metabolism. The uptake of heavy metals by plants and their subsequent accumulation in human tissues, along with biomagnification through the food chain, raise significant concerns for both human health and the environment. Heavy metals have been proven toxic to both human and environmental health. Studies have revealed that phytoremediation and microbial remediation are potential techniques for mitigating the negative effects of environmental contamination. These methods are environmentally friendly and economically effective, making them applicable to both emerging and developed nations globally. Due to the toxicity of heavy metals and their potential for bioaccumulation, mandatory monitoring of these compounds, particularly in soil and plants, is essential to prevent their entry into the human food system. Therefore, funding ongoing research and innovation in remediation technologies is crucial for addressing the expanding environmental issues of the 21st century.

REFERENCES

- Abudawood, M., Tabassum, H., Alanazi, A. H., Almusallam, F., Aljaser, F., Ali, M. N., & Al-Nuaim, L. A. A. (2021). Antioxidant status in relation to heavy metals induced oxidative stress in patients with polycystic ovarian syndrome (PCOS). *Scientific reports*, 11(1), 22935.
- Adelek B., & Abegunde, K. (2011). Heavy metal contamination of soil and ground water at automobile mechanic village in Ibadan, Nigeria. *International Journal of the Physical Sciences*, 6(5), 1045-1058.
- Agency for Toxic Substances and Disease Registry. (2003). *Toxicological profile for mercury*. U.S. Department of Health and Human Services, Centers for Disease Control.
- Alexander, P. D., Alloway, B. J., & Dourado, A. M. (2006). Genotypic variations in the accumulation of Cd, Cu, Pb, and Zn exhibited by six commonly grown vegetables. *Environmental Pollution*, 144(3), 736–745.
- Al-Naggar, Y. A., Naiem, E. A., Seif, A. I., & Mona, M. H. (2013). Honeybees and their products as a bio-indicator of environmental pollution with heavy metals. *Mellifera*, 13, 10–20.
- Alshammary, S. F., & Qian, Y. L. (2008). Long term effects of effluent water irrigation on soil nitrate and phosphorus profiles under turfgrass. *Journal of Applied Sciences*, 8, 3662-3668.
- Argun, M. E., Dursun, S., Ozdemir, C., & Karatas, M. (2007). Heavy metal adsorption by modified oak sawdust: Thermodynamics and kinetics. *Journal of Hazardous Materials*, 141, 77–85.
- Asgari Lajayer, B., Khadem Moghadam, N., Maghsoodi, M. R., Ghorbanpour, M., & Kariman, K. (2019). Phytoextraction of heavy metals from contaminated soil, water and atmosphere using ornamental plants: mechanisms and efficiency improvement strategies. *Environmental Science and Pollution Research*, 26, 8468-8484.
- Asgari, K., Najafi, P., Soleymani, A., & Larabi, R. (2007). Effects of treated municipal wastewater on growth parameters of corn in different irrigation conditions. *Journal of Biological Sciences*, 7, 1430-1435.
- Ashraf, R., & Ali, T. A. (2007). Effect of heavy metals on soil microbial community and mung beans seed germination. *Pakistan Journals of Botany*, 39(2), 629-636.
- Baritz, R., Amelung, W., Antoni, V., Boardman, J., Hijbeek, R., Horn, R., ... & Steinhoff-Knopp, B. (2023). *Soil monitoring in Europe: Indicators and thresholds for soil health assessments*. EEA Reports, 8. Publications Office of the European Union.
- Bhardwaj, J. K., Paliwal, A., & Saraf, P. (2021). Effects of heavy metals on reproduction owing to infertility. *Journal of Biochemistry and Molecular Toxicology*, 35, e22823.
- Bhattacharya, P., Welch, A. H., Stollenwerk, K. G., McLaughlin, M. J., Bundschuh, J., & Panaullah, G. (2007). Arsenic in the environment: Biology and

- chemistry. *Science of the Total Environment*, 379, 109–120.
- Bradl, H. (2005). Sources and origins of heavy metals. *Interface Science and Technology*, 6, 1-27.
- Castro-González, M. I., & Méndez-Armenta, M. (2008). Heavy metals: Implications associated to fish consumption. *Environmental Toxicology & Pharmacology*, 26, 263-271.
- Chen, G. Q., Chen, Y., Zeng, G. M., Zhang, J. C., Chen, Y. N., Wang, L., & Zhang, W. J. (2010). Speciation of cadmium and changes in bacterial communities in red soil following application of cadmium-polluted compost. *Environmental Engineering Science*, 27(12), 1019-1026.
- Chibuikwe, G. U., & Obiora, S. C. (2014). Heavy metal polluted soils: Effect on plants and bioremediation methods. *Applied Environmental Soil Science*, 12, 1-12.
- Choppala, G., Bolan, N., & Park, J. H. (2013). Chromium contamination and its risk management in complex environmental settings. *Advances in Agronomy*, 120, 129-172.
- Coetzee, J. J., Bansal, N., & Chirwa, E. M. N. (2020). Chromium in the environment, its toxic effects from chromite-mining and ferrochrome industries, and its possible bioremediation. *Exposure and Health*, 12(1), 51–62.
- Das, S., Sultana, K. W., Ndhlala, A. R., Mondal, M., & Chandra, I. (2023). Heavy metal pollution in the environment and its impact on health: Exploring green technology for remediation. *Environmental Health Insights*, 17, 11786302231201259. <https://doi.org/10.1177/11786302231201259>
- Di, D., Tooki, T., Zhou, H., *et al.* (2023). Metal mixture and osteoporosis risk: Insights from plasma metabolite profiling. *Ecotoxicology and Environmental Safety*, 263, 115256.
- Domingo, J. L. (1989). Cobalt in the environment and its toxicological implications. *Reviews of Environmental Contamination and Toxicology*, 108, 105-132. https://doi.org/10.1007/978-1-4613-8850-0_3.
- Draghici, C., Coman, G., Jelescu, C., Dima, C., & Chirila, E. (2010). Heavy metals determination in environmental and biological samples. In *Environmental heavy metal pollution and effects on child mental development: Risk assessment and prevention strategies* (pp. 123–135). NATO Advanced Research Workshop. Sofia, Bulgaria.
- Duruibe, J. O., Ogwuegbu, M. O. C., & Egwurugwu, J. N. (2007). Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences*, 2(5), 112-118.
- Elaigwu, S. E., Ajibola, V. O., & Folaranmi, F. M. (2007). Studies on the impact of municipal waste dump on surrounding soil and air quality of two cities in northern Nigeria. *Journal of Applied Sciences*, 7(3), 421-425.
- Ewubare, P. O., Omokaro, G. O., Ewansiha, O. C., & Edosa, J. O. (2023). Microbial Inoculants in Agriculture - A Microbiological Review from A Nigerian Perspective. *American Journal of Life Science and Innovation*, 2(3), 39–43. <https://doi.org/10.54536/ajlsi.v2i3.2241>
- Genchi, G., Carocci, A., Lauria, G., Sinicropi, M. S., & Catalano, A. (2020). Nickel: Human health and environmental toxicology. *International Journal of Environmental Research and Public Health*, 17(3), 679. <https://doi.org/10.3390/ijerph17030679>
- Ghoneim, A. M., Al-Zahrani, S., El-Maghraby, S., & Al-Farraj, A. (2014). Heavy metal distribution in *Fagonia indica* and *Cenchrus ciliaris* native vegetation plant species. *Journal of Food and Agricultural Environment*, 12, 320–324.
- Guala, S. D., Vega, F. A., & Coveló, E. F. (2010). The dynamics of heavy metals in plant–soil interactions. *Ecological Modelling*, 221, 1148–1152.
- Gul, I., Manzoor, M., Hashim, N., Shah, G. M., Waani, S. P. T., Shahid, M., & Arshad, M. (2021). Challenges in microbially and chelate-assisted phytoextraction of cadmium and lead—A review. *Environmental Pollution*, 287, 117667.
- Gupta, N., Yadav, K. K., Kumar, V., Prasad, S., Cabral-Pinto, M. M., Jeon, B. H., & Alsukaibia, A. K. D. (2022). Investigation of heavy metal accumulation in vegetables and health risk to humans from their consumption. *Frontiers in Environmental Science*, 10, 791052.
- Gworek, B., Dmuchowski, W., & Baczevska-Dąbrowska, A. H. (2020). Mercury in the terrestrial environment: A review. *Environmental Science and Pollution Research*, 32(1). <https://doi.org/10.1186/s12302-020-00401-x>.
- Haque, M. M., Niloy, N. M., Khirul, M. A., Alam, M. F., & Tareq, S. M. (2021). Appraisal of probabilistic human health risks of heavy metals in vegetables from industrial, non-industrial, and arsenic-contaminated areas of Bangladesh. *Helvion*, 7(5), e06309.
- Harischandra, D. S., Ghaisas, S., Zenitsky, G., Jin, H., Kanthasamy, A., Anantharam, V., & Kanthasamy, A. G. (2019). Manganese-induced neurotoxicity: new insights into the triad of protein misfolding, mitochondrial impairment, and neuroinflammation. *Frontiers in neuroscience*, 13, 654.
- Hayat, M. T., Nauman, M., Nazir, N., Ali, S., & Bangash, N. (2018). Environmental hazards of cadmium: Past, present, and future. In M.T. Hayat (Ed.), *Cadmium Toxicity and Tolerance in Plants: Agronomic, Genetic, Molecular and Omics Approaches* (pp. 163-183). <https://doi.org/10.1016/B978-0-12-814864-8.00007-3>.
- Hazarika, A., Saikia, S., Devi, B., Yadav, M., & Yadav, H. S. (2022). Oxidoreductase metalloenzymes as green catalysts for phytoremediation of environmental pollutants. In *Phytoremediation Technology for the Removal of Heavy Metals and Other Contaminants From Soil and Water* (pp. 141-172). Elsevier.
- He, M., Wang, N., Long, X., Zhang, C., Ma, C., Zhong, Q., ... Shan, J. (2019). Antimony speciation in the environment: Recent advances in understanding the biogeochemical processes and ecological effects.

- Journal of Environmental Sciences (China)*, 75, 14-39. <https://doi.org/10.1016/j.jes.2018.05.023>.
- Hegedus, C., Paşcalău, S.-N., Andronie, L., Rotaru, A.-S., Cucu, A.-A., & Dezmiorean, D. S. (2023). The journey of 1000 leagues towards the decontamination of the soil from heavy metals and the impact on the soil–plant–animal–human chain begins with the first step: phytostabilization/phytoextraction. *Agriculture*, 13, 735.
- Huang, D., Xiao, R., Du, L., *et al.* (2021). Phytoremediation of poly- and perfluoroalkyl substances: a review on aquatic plants, influencing factors, and phytotoxicity. *Journal of Hazardous Materials*, 418, 126314.
- Iannelli, M. A., Pietrini, F., Flore, L., Petrilli, L., & Massacci, A. (2002). Antioxidant response to cadmium in *Phragmites australis* plants. *Plant Physiology and Biochemistry*, 40, 977–982.
- Iwamoto, T., & Nasu, M. (2001). Current bioremediation practice and perspective. *Journal of Bioscience and Bioengineering*, 92, 1-8.
- Jaishankar, M., Mathew, B. B., Shah, M. S., & Gowda, K. R. S. (2014). Biosorption of few heavy metal ions using agricultural wastes. *Journal of Environment Pollution and Human Health*, 2(1), 1–6.
- Jebapriya, G. R., & Gnanadoss, J. J. (2013). Bioremediation of textile dye using white rot fungi: a review. *International Journal of Current Research and Review*, 5, 1.
- Jiang, W., Meng, L., Liu, F., *et al.* (2023). Distribution, source investigation, and risk assessment of topsoil heavy metals in areas with intensive anthropogenic activities using the positive matrix factorization (PMF) model coupled with self-organizing map (SOM). *Environmental Geochemistry and Health*, 45, 6353-6370.
- Jolly, Y. N., Islam, A., & Akbar, S. (2013). Transfer of metals from soil to vegetables and possible health risk assessment. *SpringerPlus*, 2(1), 385.
- Jordao, C. P., Nascentes, C. C., Cecon, P. R., Fontes, R. L. F., & Pereira, J. L. (2006). Heavy metal availability in soil amended with composted urban solid wastes. *Environmental Monitoring and Assessment*, 112, 309–326.
- Karaca, A., Cetin, S. C., Turgay, O. C., & Kizilkaya, R. (2010). Effects of heavy metals on soil enzyme activities. In I. Sheremeti & A. Varma (Eds.), *Soil heavy metals* (pp. 237–265). Soil Biology, 19. Springer.
- Kazantzis, G. (2000). Thallium in the environment and health effects. *Environmental Geochemistry and Health*, 22, 275-280. <https://doi.org/10.1023/A:1006791514080>.
- Kazemipour, M., Ansari, M., Tajrobehkar, S., Majdzadeh, M., & Kermani, H. R. (2008). Removal of lead, cadmium, zinc, and copper from industrial wastewater by carbon developed from walnut, hazelnut, almond, pistachio shell, and apricot stone. *Journal of Hazardous Materials*, 15, 322–327.
- Kesson, M. T., Point, C. C., & di Caracalla, V. D. T. (2015). *Joint FAO/WHO food standards programme codex committee on contaminants in foods*. World Health Organization.
- Khan, A., Khan, S., Khan, M. A., Qamar, Z., & Waqas, M. (2015). The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. *Environmental Science and Pollution Research*, 22, 13772-13799.
- Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z., & Zhu, Y. G. (2008). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environmental Pollution*, 152, 686-692.
- Khlifi, R., & Hamza-Chaffai, A. (2010). Head and neck cancer due to heavy metal exposure: Using *Sorghum bicolor* (L.) Moench and the microbial community response. *Environmental Pollution*, 258, 113711.
- Kimbrough, D. E., Cohen, Y., Winer, A. M., Creelman, L., & Mabuni, C. (1999). A critical assessment of chromium in the environment. *Critical Reviews in Environmental Science and Technology*, 29(1), 1-46. <https://doi.org/10.1080/10643389991259164>.
- Kothapalli, C. R. (2021). Differential impact of heavy metals on neurotoxicity during development and in aging central nervous system. *Current Opinion in Toxicology*, 26, 33–38.
- Kumar, V., & Dwivedi, S. K. (2021). Mycoremediation of heavy metals: processes, mechanisms, and affecting factors. *Environmental Science and Pollution Research*, 28, 10375-10412.
- Kumar, V., Shah, & Shahi, S. K. (Eds.). (2022). *Phytoremediation Technology for the Removal of Heavy Metals and Other Contaminants From Soil and Water*. Elsevier, 141.
- Lalor, G. C. (2008). Review of cadmium transfers from soil to humans and its health effects in the Jamaican environment. *Science of the Total Environment*, 400, 162–172.
- Li, C., Zhou, K., Qin, W., Tian, C., Qi, M., Yan, X., & Han, W. (2019). A review on heavy metals contamination in soil: effects, sources, and remediation techniques. *Soil and Sediment Contamination: An International Journal*, 28(4), 380-394.
- Li, X., Zhu, W., Meng, G., Guo, R., & Wang, Y. (2020). Phytoremediation of alkaline soils co-contaminated with cadmium and tetracycline antibiotics using the ornamental hyperaccumulators *Mirabilis jalapa* L. and *Tagetes patula* L. *Environmental Science and Pollution Research*, 27, 14175-14183.
- Lie, X. L., Gao, J., Brierley, G., Qiao, Y. M., Zhang, J., & Yang, Y. W. (2013). Rangeland degradation on the Qinghai–Tibet Plateau: Implications for rehabilitation. *Land Degradation Development*, 24, 72–80.
- Liu, Z., & Tran, K.-Q. (2021). A review on disposal and utilization of phytoremediation plants containing heavy metals. *Ecotoxicology and Environmental Safety*, 226, 112821.
- Loh, N., Loh, H.-P., Wang, L. K., & Wang, M.-H.-S. (2016). Health effects and control of toxic lead in the environment. In L. K. Wang (Ed.), *Natural resources, sustainability, and humanity* (pp. 233–284). Springer. https://doi.org/10.1007/978-3-319-26800-2_5
- Loranger, S., & Zayed, J. (1995). Environmental and occupational exposure to manganese: A multimedia

- assessment. *International Archives of Occupational and Environmental Health*, 67(2), 101-110. <https://doi.org/10.1007/BF00572233>.
- Lu, H., Shi, X., Costa, M., & Huang, C. (2005). Carcinogenic effect of nickel compounds. *Molecular and Cellular Biochemistry*, 279(1-2), 45-67. <https://doi.org/10.1007/s11010-005-8215-2>.
- Yeh, M.-H. (2005). *Environmental toxicology: Biological and health effects of pollutants* (2nd ed.). CRC Press.
- Minhas, P. S., Saha, J. K., Dotaniya, M. L., Sarkar, A., & Saha, M. (2022). Wastewater irrigation in India: Current status, impacts and response options. *Science of the Total Environment*, 808, 152001.
- Mohan, I., Gorla, K., Dhar, S., Kothari, R., Bhau, B., & Pathania, D. (2021). Phytoremediation of heavy metals from the biosphere perspective and solutions. In *Pollutants and water management: Resources, strategies, and scarcity* (pp. 95–127). Springer.
- Mojiri, A., & Amirossadat, Z. (2011). Effects of urban wastewater on accumulation of heavy metals in soil and corn (*Zea mays* L.) with sprinkler irrigation method. *Asian Journal of Plant Science*, 10, 233-237.
- Morgan, R. (2013). Soil, heavy metals, and human health. In E. C. Brevik & L. C. Burgess (Eds.), *Soils and human health* (pp. 59-82). CRC Press.
- Mukherjee, A. B., Zevenhoven, R., Bhattacharya, P., Sajwan, K. S., & Kikuchi, R. (2008). Mercury flow via coal and coal utilization by-products: A global perspective. *Resources, Conservation and Recycling*, 52, 571-591.
- Muthusamy, L., Rajendran, M., Ramamoorthy, K., Narayanan, M., & Kandasamy, S. (2022). Phytostabilization of metal mine tailings—A green remediation technology. In *Phytoremediation technology for the removal of heavy metals and other contaminants from soil and water* (pp. 243–253). Elsevier.
- Nebeská, D., Trögl, J., Ševců, A., Špánek, R., Marková, K., Davis, L., & Pidlisnyuk, V. (2021). *Miscanthus x giganteus* role in phytodegradation and changes in bacterial community of soil contaminated by petroleum industry. *Ecotoxicology and Environmental Safety*, 224, 112630.
- Nedjimi, B. (2021). Phytoremediation: A sustainable environmental technology for heavy metals decontamination. *Applied Sciences*, 3(1), 1–19.
- O’Neal, S. L., & Zheng, W. (2015). Manganese toxicity upon overexposure: A decade in review. *Current Environmental Health Reports*, 2(3), 315-328. <https://doi.org/10.1007/s40572-015-0056-x>.
- Omokaro, G. O. (2024). Farmers’ perceptions of pest and disease control methods in South-South Nigeria. *Acta Biology Forum*, 4(1), 11–15.
- Omokaro, G. O., Ojugh, M. G., Michael, I., & Nafula, Z. S. (2023). Heavy Metal Concentration of Okra (*Abelmoschus Esculentus*) Grown on Dumpsite Soil in Benin City, Nigeria. *American Journal of Food Science and Technology*, 2(2), 65–73. <https://doi.org/10.54536/ajfst.v2i2.2233>
- Omokaro, G. O., & Nafula, Z. S. (2023). Microalgae - Harnessing Environmental and Nature Benefits – A Comprehensive Review. *American Journal of Agricultural Science, Engineering, and Technology*, 7(3), 47–56. <https://doi.org/10.54536/ajaset.v7i3.2232>
- Papafilippaki, A., Kotti, M., & Stavroulakis, G. (2008). Seasonal variations in dissolved heavy metals in the Keritis River Chania, Greece. *Global Nest Journal*, 3, 320-325.
- Pete, A. J., Bharti, B., & Benton, M. G. (2021). Nano-enhanced bioremediation for oil spills: a review. *ACS ES&T Engineering*, 1, 928-946.
- Peter, A. L. J., & Viraraghavan, T. (2005). Thallium: A review of public health and environmental concerns. *Environment International*, 31(4), 493-501. <https://doi.org/10.1016/j.envint.2004.09.003>.
- Pouresmaeli, M., Ataei, M., Forouzandeh, P., Azizollahi, P., & Mahmoudifard, M. (2022). Recent progress on sustainable phytoremediation of heavy metals from soil. *Journal of Environmental Chemical Engineering*, 10, 108482.
- Pourret, O., Bollinger, J. C., & Hursthouse, A. (2021). Heavy metal: a misused term? *Acta Geochim*, 40, 466-471.
- Qasem, N. A. A., Mohammed, R. H., & Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: A comprehensive and critical review. *NPJ Clean*, 4, 1-15.
- Rascio, N., & Izzo, F. N. (2011). Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting? *Plant Science*, 180, 169–181.
- Rees, N., & Fuller, R. (2020). *The toxic truth: Children’s exposure to lead pollution undermines a generation of future potential*. UNICEF.
- Rice, K. M., Walker, E. M., Wu, M., Gillette, C., & Blough, E. R. (2014). Environmental mercury and its toxic effects. *Journal of Preventive Medicine and Public Health*, 47(2), 74-83. <https://doi.org/10.3961/jpmph.2014.47.2.74>.
- Schwartz, G. G., Il’yasova, D., & Ivanova, A. (2003). Urinary cadmium, impaired fasting glucose, and diabetes in the NHANES III. *Diabetes Care*, 26(2), 468-470. <https://doi.org/10.2337/diacare.26.2.468>.
- Sharma, P. (2021). Efficiency of bacteria and bacterial assisted phytoremediation of heavy metals: An update. *Bioresource Technology*, 328, 124835.
- Shourie, A., & Vijayalakshmi, U. (2022). Fungal diversity and its role in mycoremediation. *Geomicrobiology Journal*, 39, 426-444.
- Shun-hong, H., Bing, P., Zhi-hui, Y., Li-yuan, C., & Li-cheng, Z. (2009). Chromium accumulation, microorganism population and enzyme activities in soils around chromium-containing slag heap of steel alloy factory. *Transactions of Nonferrous Metals Society of China*, 19, 241-248.
- Singh, P., Raghukumar, C., Parvatkar, R. R., & Mascarenhas-Pereira, M. B. (2013). Heavy metal

- tolerance in the psychrotolerant *Cryptococcus* sp. isolated from deep-sea sediments of the Central Indian Basin. *Yeast*, 30(2), 93–101.
- Sobha, K., Poornima, A., Harini, P., & Veeraiyah, K. (2007). A study on biochemical changes in the fresh water fish, *Catla catla* (Hamilton) exposed to the heavy metal toxicant cadmium chloride. *Kathmandu University Journal of Science, Engineering and Technology*, 1(4), 1-11.
- Stern, B. R., Solioz, M., Krewski, D., Aggett, P., Aw, T. C., Baker, S., Crump, K., Dourson, M., Haber, L., Hertzberg, R., Keen, C., Meek, B., Rudenko, L., Schoeny, R., Slob, W., & Starr, T. (2007). Copper and human health: Biochemistry, genetics, and strategies for modeling dose-response relationships. *Journal of Toxicology and Environmental Health, Part B*, 10, 157–222.
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. In A. Luch (Ed.), *Molecular, clinical and environmental toxicology. Experientia supplementum* (Vol. 101, pp. 133-164). Springer.
- UNEP/GPA. (2006). *The state of the marine environment: Trends and processes*. UNEP/GPA.
- Velusamy, S., Roy, A., Sundaram, S., & Kumar Mallick, T. (2021). A review on heavy metal ions and dyes removal through graphene oxide-based adsorption strategies for textile wastewater treatment. *The Chemical Record*, 21(7), 1570–1610.
- Vieira, C., Morais, S., Ramos, S., Delerue-Matos, C., & Oliveira, M. B. P. P. (2011). Mercury, cadmium, lead and arsenic levels in three pelagic fish species from the Atlantic Ocean: Intra- and inter-specific variability and human health risks for consumption. *Food and Chemical Toxicology*, 49, 923-932.
- World Health Organization (WHO). (2004). *Guidelines for Drinking-Water Quality*. World Health Organization
- World Health Organization. (1996). *Permissible limits of heavy metals in soil and plants*. World Health Organization.
- Wong, J. W. C., & Selvam, A. (2006). Speciation of heavy metals during co-composting of sewage sludge with lime. *Chemosphere*, 63, 980–986.
- Wu, Y. (2014). General standard for contaminants and toxins in food and feed. *Codex stan*, 193-1995.
- Yaashikaa, P. R., Kumar, P. S., Jeevanantham, S., & Saravanan, R. (2022). A review on bioremediation approach for heavy metal detoxification and accumulation in plants. *Environmental Pollution*, 301, 119035
- Yao, H., Xu, J., & Huang, C. (2003). Substrate utilization pattern, biomass and activity of microbial communities in a sequence of heavy metal-polluted paddy soils. *Geoderma*, 115, 139–148.
- Zabalawy, E. M. Kh., Abou-Shleel, M. S., & Abdel-Kareem, S. M. (2015). Effect of marine on bio-accumulation of heavy metals from polluted soil by some leafy vegetables. *Nature and Science*, 13(3), 109-116.
- Zhang, I., & Wong, M. H. (2007). Environmental mercury contamination in China: Sources and impacts. *Environment International*, 33, 108-121.
- Zhang, X., Yang, L., Li, Y., Li, H., Wang, W., & Ye, B. (2012). Impacts of lead/zinc mining and smelting on the environment and human health in China. *Environmental Monitoring and Assessment*, 184(4), 2261-2273. <https://doi.org/10.1007/s10661-011-2115-6>.
- Zhu, G., Liu, W., Wen, Y., Liao, X., & Sun, L. (2021). Potential of arsenate-reducing bacterial inoculants to enhance field-scale remediation of arsenic contaminated soils by *Pteris vittata* L. *Ecological Engineering*, 169, 106312.