World Nutrition 2025; 16(1):49-76

Review

Bioremediation of Heavy Metal Contaminated Soils in Sub-Saharan Africa: Implications for Food Safety and Public Health Nutrition

Iyadunni Adesola ANUOLUWA[1*]; Boluwatife Stephen ANUOLUWA[2]; Zaccheus Sunday OLOLADE[3] and Adebanke Mayomi AJAGUNNA[1]

[1]Department of Microbiology, Faculty of Sciences, University of Medical Sciences, Ondo State, Nigeria
[2]Department of Environmental Health Sciences, School of Public Health, University of Medical Sciences, Ondo State, Nigeria
[3]Department of Chemistry, Faculty of Sciences, University of Medical Sciences, Ondo State, Nigeria.

[*]Corresponding author: ianuoluwa@unimed.edu.ng; dunnibright@yahoo.com

Abstract

Most Sub-Saharan African nations are faced with increasing build-up coupled with persistence of compounds which are toxic in their soil. These persistent toxic materials constitute a significant danger to the environment. Heavy metals are major contaminants consistently found in sediments, air, water, and soil and has bio-accumulative potential in the food chain. They often enter the environment as a consequence of industrial processes such as electroplating, extraction and refining of mineral ores etc. Heavy metals accumulate in some plants, leading to biomagnification in humans when such plants are consumed, creating a serious threat to food safety and public health. At minute levels, some heavy metals are co-factors partaking in the production of enzymes in the body. Occurrence of these metals above threshold limits can be responsible for their behaving in a deleterious manner in which they displace other metal ions, block specific functional groups, or modify the active configuration of some molecules needed for biological functions The use of technologies such as excavation, soil washing, incineration, landfilling and soil flushing in treating soils contaminated with heavy metals is not cost effective and also not environmentally friendly. Bioremediation which is the use of microorganisms facilitates the breakdown of environmental contaminants like organic wastes and heavy metals to an innocuous state under controlled conditions, Various microorganisms have been used in attenuating the harmful effects of heavy metals in the environment and the process have been observed to be an eco-friendly and cost-effective substitute to the conventional treatment approaches and it enhances both the soil quality and its usage, especially in Sub-Saharan African nations. This review is consequently focusing on the impact of microorganisms in bioremediation.

Keywords: heavy metals, accumulation, Sub-Saharan Africa, bioremediation, bioaccumulation, biomagnification

Introduction

Human exposure to heavy metals is one of the greatest health risks in Sub-Saharan Africa, attracting the attention of environmentalists and other concerned groups on a national and worldwide level. The ongoing geometric increase in population has led to increased urbanization, coupled with increased creation of slums and sub-town settlements resulting from poor urban planning and resource allocation. The aftermath of these trends is waste generation at an accelerating rate without adequate waste management systems.

A report jointly produced by United Nations Environment Program (UNEP) and International Solid Waste Association (ISWA) estimated an increase in the volume of municipal solid waste (MSW) generated worldwide from 2.3 billion tonnes in 2023 to 3.8 billion tonnes in 2050 out of which only 19% is being recycled (UNEP 2024). Combustion of toxic wastes, increased unregulated mining, indiscriminate dumping of waste, use of leaded gasoline, location and concentration of manufacturing factories within residential areas, together with weak environmental pollution laws, are all proven agents of soil, air, water, and food product contamination, and they are all significant contributors to the unusual surge in heavy metal pollution experienced over the past few years (Fasinu and Orisakwe 2013; Putri et al. 2024). Oberg et al. (2011) estimated that 25% of the total burden of diseases and about 2.97 million cases of human death are attributable to environmental risk factors, including those resulting from heavy metals contamination.

Heavy metals have been defined as elements that have more than 20 electrons with density higher than 5 g/cm^3 or 5 mg/mL (Jarup 2003; Witkowska et al. 2021). They possess characteristics such as electropositivity, density, ductility, conductivity, and ligand-specificity. Heavy metals include molybdenum, lead, vanadium, arsenic, chromium, zinc, copper, nickel, and cadmium, as well as, cobalt, aluminium, and strontium (Mitra et al. 2022). A number of metals are involved in important roles in biological system functions such as enzyme production or function but must be available only within a particular concentration range. Some heavy metals supply essential cofactors for metalloproteins and enzymes and as such decreased metabolic activity can result if their concentration is low. However, occurrence of these metals above threshold limits can be responsible for their behaving in a deleterious manner in which they displace other metal ions, block specific functional groups, or modify the active configuration of some molecules needed for biological functions (Bharti and Sharma 2021; Jomova et al. 2022).

Heavy metals typically exist in freshwater ecosystems at relatively low amounts (Le Faucheur et al. 2006). As illustrated in Figure 1, human activities cause these levels to rise. Electroplating, tanning of leather, preparation of chrome, finishing of metal, mills where steel is rolled, and production of materials such as pigments, stabilizers, batteries, fertilizers, and alloys may release their wastewaters into the environment and this significantly impacts both the aquatic and soil habitats negatively (Stephens and Calder 2005; Osibote et al. 2014). Smelting and mining operations tend to include activities such as excavation of minerals, transportation of ore, refining of the ore, tailings, and waste water disposal around mines (Navarro et al. 2008; Lu et al. 2015; Mackay et al. 2013; Podolský et al. 2015; Strzebońska et al. 2017).

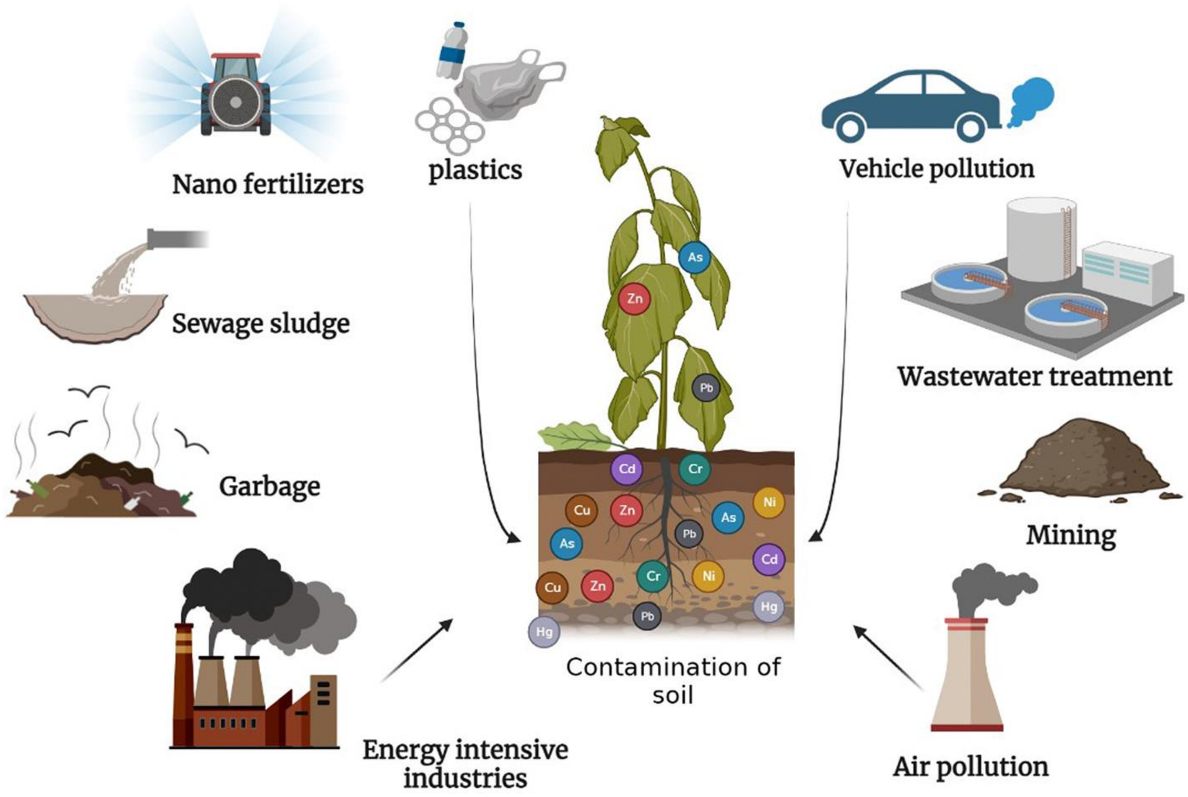

Figure 1. Anthropogenic sources of heavy metals (Adapted from Angon et al. 2024)

The resulting environmental lead, cadmium, copper, mercury, and chromium have grave health implication on those living nearby (Suruchi and Khanna 2011; Ali et al. 2022; Ogbeide and Henry 2024). Routes of human exposure to these contaminants include breathing of air laden with particles or gaseous forms of these metals, eating and drinking contaminated food or water, and skin contact with these metals (Masindi and Muedi 2018). Health risks from less than lethal levels of mercury, lead, and arsenic include headaches, cramping in the abdomen, diarrhoea, weakness, a decline in mental capacity, harm to the kidneys, and eventually irreversible damage to the brain and kidney (USEPA 2004; Witkowska et al. 2021).

Sites contaminated with heavy metals have been treated using techniques, such as ion exchange, excavation and landfilling, soil incineration, chemical precipitation, reverse osmosis, soil washing and flushing, solidification and stabilization, electro-kinetic systems, and recovery through evaporation (Zhu et al. 2004; Huang et al. 2012, Song et al. 2022; Aziz et al. 2023). These techniques are not environmentally friendly and are costly as well. Thus, there is a need for using an economical and environmentally beneficial method to address this threat (Gavrilescu 2004; Malik 2004; Ojuederie and Babalola 2017, Rodríguez-Eugenio et al. 2018, Song et al. 2022).

Bioremediation, otherwise termed bioreclamation and biorestoration, is the intentional use of indigenous microbial organisms found in a contaminated environment to ameliorate the effects of contaminants in such environment while converting the contaminants to less harmful products in the process (Bala et al. 2022; Ikhimalo and Ugbenyen 2023). It facilitates the breakdown of environmental contaminants like organic wastes and heavy metals to an innocuous state under controlled conditions. Bioremediation usually adjusts the air, nutrient, and water supply so as to promote the biological metabolism of the contaminants.

Biostimulation, which involves adding lignocellulosic materials like wood chips that supply nutrients such as nitrogen, phosphorus, and potassium (N/P/K) and/or bulking agents to the native microorganisms; or bioaugmentation, introduction into the contaminated environment of microorganisms with known abilities to degrade the pollutant, are two techniques that can be used to achieve bioremediation (Bamforth and Singleton 2005).

The fact that they are not biodegradable is a crucial factor to take into account in heavy metals remediation. The goal instead becomes to have them undergo changes in valence state, sorption, methylation, complexation, and other processes that impact their bioavailability and mobility. Detoxification of heavy metal contaminated sites and prevention of further spread thus can be achieved using microorganisms which possess the capability to alter how reactive and mobile heavy metals are. Some of the bacteria with recognized bioremediation capacity, particularly in for cadmium, include *Bacillus, Staphylococcus, Citrobacter, Klebsiella, Pseudomonas*, and *Rhodococcus* (Kozlowski and Walkowrak 2002). *Pseudotmonas and Alcaligenes* have been applied in the bioremediation of chromium (Kozlowski and Walkowrak 2002), andbacterial isolates such as *Pseudomonas* and *Escherichia* have been applied in bioremediating copper (Kozlowski and Walkowrak 2002).

Methods

The scientific databases we searched were Google Scholar, Web of Science, Springer Link, Wiley Online Library, and Mendeley. The keywords searched for were "heavy metals", "food chain", "agricultural soil", "plants", "HMs", "soil contamination" “bioremediation” and "impact of heavy metals.”. Literature that was considered and used for this review met the following criteria: (i) the study mentioned the sources of heavy metals in the environment (ii) the study describes the effect of heavy metals on plants, microorganisms or humans (iii) the study focused on the methods used in removing heavy metals from the environment (iv) the study included the impact of heavy metals on nutrition, food safety and security. Consequently, this review has made efforts to put together literature on the effects of heavy metals, sources of heavy metals, the presence of heavy metals in food chains and plants, soil and water, and methods used in the treatment of heavy metals contaminated soil.

REVIEW FINDINGS

Heavy metals sources in the Sub-Saharan Africa

Various natural occurrences and anthropogenic activities account for the availability of heavy metals in the environment; some of which are shown in Table 1. Anthropogenic activities have the potential to counteract the absorption of heavy metals by altering the organic matter, bioavailability, and pH of heavy metals in the soil, making them more pervasive in the rest of the environment (Yusuf and Osibajo 2006; Alengebawy et al. 2021; Das et al. 2023). Some ions of base and heavy metals are plant micronutrients in the soil (Alloway 2013). Although the level of soil contamination they cause is quite minute, as a result of pollution, the environmental quality is frequently worse in larger metropolitan areas (Eddy 2004).

Mining activities are widespread in Sub-Saharan Africa, often with detrimental environmental consequences (Omotehinse and Ako 2019) due to poor regulatory mechanisms and legislation. Mine tailings, which are toxic mining wastes primarily composed of tiny particles with varying amounts of heavy metals, are frequently accumulated and can spread to reach agricultural soils through wind and water erosion. Some agricultural fields in Namibia close to tailing dams had high levels of lead and copper (Mileusnić et al. 2014). In India, high levels of nickel and chromium were observed in agricultural soils close to abandoned chromite-asbestos mine waste and in crops cultivated on such soils (Kumar and Maiti 2015).

Table 1. Heavy metal sources in the environment

Heavy Metals	Anthropogenic sources	Natural sources
Lead	Combustion of leaded gasoline, battery waste, insecticides, and herbicides contribute to air pollution	
Arsenic	Pesticides, biosolids, smelting, and mining processes, as well as use of wood preservatives	Minerals weathering
Chromium	Fly ash, tanneries, steel factories	Biogenic sources and forest fires
Cadmium	Paints and pigments, acrylic stabilizers, electroplating, fertilizers with phosphates	Erosion and volcanic activity
Mercury	Mining of silver-gold, combustion of coal, wastes from medical sources	
Copper	Pesticides, fertilizers, mining, and smelting operations, as well as biosolids	Vegetation-related particles
Nickel	Wastewater, kitchen appliances, medical devices, automobile batteries	

Adapted from Dixit et al. 2015.

An example of harm in an urban area is the metal poisoning at Minamata which happened in the 1960s and in which thousands of lives were lost in Japan. A similar incident was lead poisoning in Nigeria in the early months of 2010, which resulted in the death of about 400 children under the age of five and the permanent disability of more than 2,000 youngsters (Fasinu and Orisakwe 2013; Wilcox et al. 2008; Kaufman et al. 2016).

Disposal of municipal wastes in most communities in Sub-Saharan Africa is done using informal or illegal landfills. Some industries in some Sub-Saharan African countries also release untreated wastewater into the environment; an example is the release of effluents without proper treatment from textile industries which is a significant source of contamination inadvertently increasing the heavy metals burden in the environment (Osibote et al. 2014; Rodríguez-Eugenio et al. 2018).

The recycling of lead batteries disposes of wastes into the environment (Gottesfeld et al. 2018). Wastes arising from spoilt and discarded electronics otherwise called e-wastes contain essential materials such as copper and gold, plus more toxic contaminants than regular urban waste. Itai et al. (2014) noted the presence of high heavy metals concentrations and rare metalloids such as Bi, In, and Sb at a site recycling e-waste in Ghana. The bulk of electronic waste is still not recycled (Barba-Gutiérrez et al. 2008; Sthiannopkao and Wong 2013).

Heavy metals can affect soil quality adversely, especially soil used for farming purposes, causing phytotoxicity and heavy metal transfer from crop uptake to the diet of humans (Nicholson et al. 2003). It is common practice in agriculture to use sewage sludge as an organic soil supplement since it enriches the soil with nutrients and organic matter. However, failure to pre-treat the sewage sludge results in the accumulation, of many pollutants, including heavy metals, eventually affecting the food chain (Buta et al. 2021; Tindwa and Singh 2023). A survey by Cang et al. (2004) found soil contamination arising from dumping poultry and livestock wastes contained the trace heavy metals used as supplements to and contaminants in their feeds (Aljohani 2023). These other processes increase the assimilation of heavy metals into food crops (Chen et al. 2005; Singh et al. 2004, Alengebawy et al. 2021, Angon et al. 2024), especially when soils have a low pH (Dinev and Bojinova 2006). Intricate processes such as heavy metal uptake and build-up in plants are determined by the property of the metal, the characteristics of the soil and the properties of the biological agent (Japenga et al. 2005; Dinev and Vassilev 2006).

The different chemical forms that heavy metals can take in soil can determine how soluble they are, which directly affects how mobile they are and how readily available to living things. For instance, due to the high mobility of cadmium in soil, it is readily assimilated by plants (Di Toppi et al. 1999; Bharti and Sharma 2021). The soil's pH, cation exchange capacity, clay content, organic carbon content, and redox conditions are the main determinants of metal solubility in soil (Hough et al. 2003; Walker et al. 2003; Kashem and Singh 2004; Rieuwerts et al. 2006). For instance, metal cations are mobile at pH ranges of 4.0-8.5, while anions appear to turn into minerals with oxides. Cations are activated at high pH levels and this facilitates their adsorption to metal anions and mineral surfaces. Iron and manganese, as well as aluminium hydrous oxides, can impact metal concentrations because they have the ability to remove cations and anions.

Adverse effects of heavy metals due to bioaccumulation

Heavy metals are extremely harmful because they have long biological half-lives and the capacity to bioaccumulate in many organs of plants, animals, and people due to their non-biodegradable nature. The toxicity of many heavy metals is enhanced as a result of their solubility in water, causing them to be harmful even at low concentration because there is no effective method of removing them once they get into the body (Abii 2012). They can also precipitate on surfaces, for example from air pollution, before being absorbed by the tissues of vegetables (Suruchi and Khanna 2011, Kkairiah et al. 2004; Al-Jassir et al. 2005; Singh and Kumar 2006; Kachenko and Singh 2006, Sharma et al. 2008a, 2008b). Heavy metals may have a negative effect on different tissues, reproduction and growth in humans and can lead to anaemia, nervous system diseases and weakened immune systems (Balali-Mood et al. 2021).

Heavy metals impact on microorganisms

Metals are an important part of the life-cycles of microorganisms, for example serving as micronutrients used in redox processes. They also serve as components of various enzymes, stabilize molecules through electrostatic interactions, and regulate osmotic pressure. However, some are not biologically essential and potentially harmful to micro-organisms (Bruins et al. 2000). The toxicity exhibited by non-essential metals is caused by the removal of essential metals from their native binding sites or by interactions with ligands (Nies 1999; Bruins et al. 2000). Metals like Ag^{2+}, Cd^{2+} and Hg^{2+} appear to bind to sulphur hydryl (SH) groups and thus inhibit sensitive enzyme activity (Nies 1999).

The biomass of microorganisms in soils contaminated with metals has been observed to show substantial decrease compared to uncontaminated soils (Frostegård et al. 1993; Fliessbach et al. 1994; Roane and Kellogg 1996; Konopka et al. 1999; Igiri et al. 2018). Metal pollution in the soil causes a change from sensitive microbes to less sensitive ones (Roane and Kellogg 1996; Dahlin et al. 1997; Bååth et al. 1998a, 1998b; Khan and Scullion 2000).

At high concentrations, heavy metals which are grouped as non-essential or essential have the tendency to alter the specificity of enzymes; damage cellular membranes; interrupt cell functions; and damage DNA structure (Bruins et al. 2000). For most metal ions to exert a physiological or toxic effect on microorganisms, they must penetrate the microbial cell. Because ions of heavy metals cannot be degraded or modified compared to the toxic organic compounds, microorganisms develop some form of resistance to them by using one or more mechanisms such as exclusion of the ions from microbial system by using permeability barrier, use of intracellular and extracellular sequestration, development of active efflux pumps, reducing the heavy metal ions enzymatically and reduction of the target cell sensitivity to metal ions. The existence of any or a combination of these mechanisms enables the development and survival of microorganisms in metal contaminated environments (Ji and Silver 1995; Nies and Silver 1995; Rensing et al. 1999; Chu 2018; Hu et al. 2021; Syed et al. 2021).

Impact of heavy metals on plants

Vegetables are essential parts of the human diet. Hence, the occurrence of heavy metals in them cannot be overlooked (Marshall 2004; Radwan and Salama 2006; Wang et al. 2005; Khan et al. 2008). Depending on the level of consumption, heavy metals become biomagnified in humans (Brevik 2013; Burgess 2013; Jordão et al. 2006; Pan et al. 2010).

Some factors which determine the biotoxicity effects of heavy metals on plants include the source of the heavy metals, the concentration, oxidation states and how it is been deposited on plant (Duruibe et al. 2007). Various factors such as climate, nature of the soil, atmospheric deposition, degree of plant maturity at harvest time, and heavy metal concentration in the soil, all play a part in affecting the absorption and bioaccumulation of heavy metals in vegetables (Anuoluwa et al. 2021). Waste water usage either in its untreated or treated form over an extended period of time in agriculture can have an impact (Adeniyi 1996; Sinha et al. 2005; Sharma et al. 2006). Therefore, it is imperative that the heavy metal content in soil fertigated with waste water is monitored in order to guard against the introduction of heavy metals into the food chain (Dudka and Miller 1999).

At higher levels, heavy metals present in the soil inhibit some plant activities such as root growth, shoot development and processes involved in plant metabolism, resulting in a reduction in the ability of the plant to absorb nutrients and water, damage to the enzyme system, and chlorosis (Sanità di Toppi and Gabbrielli 1999; Yang et al. 2020; Anuoluwa et al. 2021). Shukla et al. (2007) noted that due to the high toxicity of cadmium (Cd) and chromium (Cr) to plants, even in minute concentrations, they are of specific concern among the heavy metal elements. Cadmium, due to its high solubility and water toxicity, has been classified as a hazardous pollutant (Pinto et al. 2004; Haider et al. 2021).

High concentration of lead in the soil increases the reactive oxygen species production which causes damage to chlorophyll and lipid membrane during photosynthetic processes and overall plant growth (Najeeb et al. 2017).

Consuming plants with high concentrations of these heavy metals can pose serious health risks to humans (Cui et al. 2004), depending on the heavy metal's physical characteristics, its chemical composition, the type of vegetable and the amount consumed (Anuoluwa et al. 2021). In recent years, the consumption rate of vegetables has increased, due to increased awareness of the nutritional value of the compounds present in vegetables which are essential for human survival and are protective against certain diseases (Badawy and El-Motaium 2003). Thus, information on concentrations of heavy metals in food products and their intake levels is very important in the assessment of risk to human health (Mushtaq and Khan 2010).

Impact of heavy metals on humans

Some metals can be carcinogenic, mutagenic, or toxic, even at very minute concentrations (Picardo et al. 2009). As illustrated in Figure 2, humans are usually exposed to heavy metal contamination through ingestion of food and water, air, or contact with the skin. Metals like arsenic, lead and mercury are dangerous to the kidneys, capable of decreasing mental capacity, cause weakness, headaches, cramps in the abdomen, diarrhoea, and anaemia. Lead and cadmium are potential carcinogens and are able to cause blood, bone, cardiovascular, nervous, and kidney diseases (Jarup 2003). Exposure to these metal contaminants over an

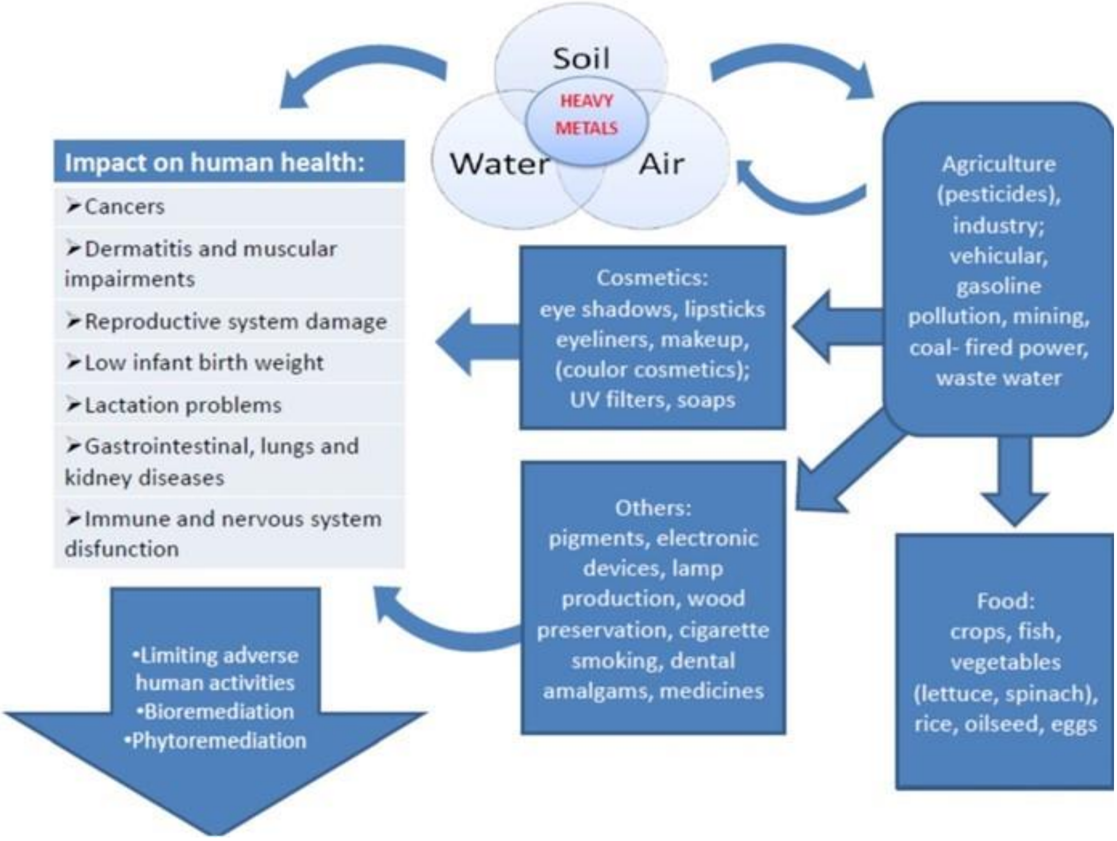

Figure 2. Routes of human exposure to heavy metals and various health implications (adapted from Witkowska et al. 2021).

extended period of time can cause permanent damage to the kidneys and brain (USEPA 2004). Consumption of food contaminated with Pb, As, Hg, cadmium and other metals also can deplete body stores of vitamin C, iron, and other essential nutrients (Iyengar and Nair 2000).

Lead is harmful even at very low concentrations. It can cause damage to the nervous system, bone, liver, pancreas, teeth, and gum (Bakidere and Yaman 2008; Fergusson 1990), as well as lungs, kidneys liver, and spleen where it causes biochemical imbalances and neurotoxicity, especially in children and infants (Guerra et al. 2012; Jaishankar et al. 2014).

Though metals such as copper and zinc are important elements necessary for the proper physiological functions of the body, their occurrence at high levels in feed plants and food can produce toxicity effects in human and animal (Kabata-Pendias and Mukherjee 2007). Zinc can cause anaemia and tissue lesions; negative effects from copper are rare, but prolonged exposure in infants may result in liver and kidney damage (Brevik 2013).

Skin contact with nickel on coin and jewellery is dermatitis (nickel itch). High concentrations of Nickel cause cancer of the nose, lungs, and bone. Ingestion of water containing high levels of Ni (II) can cause nausea, pulmonary fibrosis, renal oedema, gastrointestinal distress, vomiting, diarrhoea, skin dermatitis and serious harm to the lungs and kidneys (Erdogan et al. 2005; Meena et al. 2005). Long-term exposure to nickel can cause abnormalities and neurological consequences in liver, hepatic and kidneys (Brevik 2013).

Organomercuric compounds, particularly methylmercury, are highly toxic. They can accumulate in fish in some contaminated water bodies. Ingestion of such fish, especially by pregnant women, is dangerous both to them and the foetuses, causing alterations in neural and gastric systems and even death (Chen and Dong 2022; Dragan et al. 2023). Ingested or inhaled arsenic is primarily stored in the lungs, heart kidneys, and liver while smaller concentrations may be stored in the nerve tissue and muscle. Arsenic is also known to be carcinogenic. It may cause anaemia, skin cancer, liver and kidney failure and disorders in the nervous systems (Brevik 2013).

Methods used in remediation

Metal pollution persists and accumulates in the environment because they cannot be destroyed chemically or biologically. Thus, heavy metals cannot be chemically or biologically eliminated -- but can be converted from an oxidation state to another (Knox et al. 2000). By altering their oxidation state, heavy metals may become:

i. more soluble in water and extracted by leaching
ii. potentially less toxic
iii. less soluble in water, forming precipitates that makes them less bioavailable and easier to extract from the polluted site
iv. volatilized and expunged from the contaminated site (Garbisu and Alkorta 1997).

The approaches commonly employed in remediation of heavy metals are: isolation of the contaminating metals, immobilizing or mobilizing the metals, physical separation, and extraction (Evanko and Dzombak 1997). Each of these techniques has its own particular advantages and limitations (MADEP 1993), and most industries employ a combination of approaches. Two of these approaches, mobilization, and immobilization, are commonly used for bioremediation processes.

Microbial remediation (Bioremediation)

Bioremediation involves the microbial degradation of pollutants via the metabolism of the microorganisms, and is thus carried out through various biochemical pathways that are related to the growth and activity of the microorganisms. By using co-metabolism processes, microorganisms degrade toxic substances found in contaminated environments into harmless metabolites (Ojuederie and Babalola 2017).

The technology of bioremediation involves using microorganisms in reducing, removing, containing, or transforming contaminants present in environments such as water, sediments, soils, and air into products which do not constitute any serious threat to the environment (NABIR 2003). Bioremediation can be said to be an innovative and promising technology that can be applied in/on polluted water and land to remove and recover heavy metals. Most microorganisms found in heavy metal-polluted habitats have developed survival strategies. Some can detoxify heavy metals.

These strategies include biotransformation, biosorption, bioaccumulation, and biomineralization, which can be used either in situ or ex situ (Gadd 2000; Lim et al. 2003; Malik 2004; Lin and Lin 2005). Microorganisms are able to assimilate heavy metals actively which is also referred to as bioaccumulation and/or passively which is referred to as adsorption (Hussein et al. 2001). Some constituents of the microbial cell wall (lipids, polysaccharides, and proteins) possess functional groups which can attach to heavy metal ions (Scott and Karanjkar 1992), affecting the mobility and reactivity of the metals.

Bioremediation processes promote the growth of such microorganisms by allowing them to utilize the contaminants present in the polluted environment as sources of energy and carbon. In most cases, microorganisms which are indigenous to the contaminated sites are used and they are provided with optimum nutrients and other chemicals required for their metabolism so that they can perform efficiently (Iram et al. 2009; Ajaz et al. 2010). Bioremediation strategies utilize bioaugmentation, in which the supplies of water, air and nutrients are adjusted. This is usually accomplished through biostimulation, the addition of bulking agents such as wood chips and/or nutrients such as nitrogen, potassium, and phosphorus (Bamforth and Singleton 2005).

Application of bioremediation often involves manipulating environmental markers so that microbial degradation and growth can proceed more rapidly. The process becomes effective where and when the conditions of the environment both allow its application and also encourage the growth and activity of microorganisms (Fulekar 2010). Although most microorganisms can detoxify many contaminants by mineralizing, transforming, and/or immobilizing the contaminants, bacteria generally play a crucial role in this process (Diaz 2004; Das et al. 2023). This is because most bacteria species have developed strategies which enables them to obtain energy from almost any compound under anoxic or oxic situations by using alternative final electron acceptors such as sulphate, nitrate, and ferric ions (Ferhan et al. 2002).

Microorganisms can detoxify metals using volatilization, valence transformation, extracellular chemical precipitation orenzymatic reactions, reducing certain heavy metals in metabolic processes which are not linked to heavy metal assimilation (Lovley 1993; Bala et al. 2022). Many microorganisms also produce siderophores, molecules which form complexes with iron, some of which have a high affinity for heavy metals. For example, the synthesis of siderophore in *Pseudomonas aeruginosa* and *Alcaligenes eutrophus* can be induced by high concentrations of iron (Höfte et al. 1994; Gilis et al. 1996). Bioprecipitation, a process that converts sulfate to hydrogen sulphide, which when reacted with heavy metals, forms insoluble metal sulfides, can be achieved by sulphate-reducing bacteria (White et al. 1998; Iwamoto and Nasu 2001).

The application of GEMs in bioremediation

As a result of advances in modern genetic and omics techniques such as proteomics, metabolomics and genomics, the physiology of microorganisms linked to the elimination of pollutants from the environment can now be extensively studied using whole genome sequencing (Buermans and Den Dunnen 2014; Ghosal et al., 2016). The characterization of genes encoding bacterial transformation inorganically, has charted the potential use of molecular genetics to improve heavy metal tolerance (Mani and Kumar, 2014). Genetic engineering has provided microorganisms which possess higher environmental clean-up potentials than indigenous microorganisms.

Genetically engineered microorganisms (GEMs or GMOs) have been applied in the bioremediation polluted environments such as aquifers, soil and activated sludge environments and they have exhibited enhanced capabilities for degradation on a wide spectrum of chemical pollutants (Abatenh et al. 2017; Dixit et al. 2015*;* Ojuederie and

Babalola 2017). For example, rate-limiting steps in known metabolic pathways can be genetically manipulated to deliver increased rates of degradation. Also, bacterial strains can be modified to have entirely new metabolic pathways which can enable them to degrade compounds which were previously known to be recalcitrant. Four important strategies commonly implemented in GEMs are: (1) application of bioaffinity sensors for chemical sensing, end-point analysis and toxicity reduction; (2) regulation and construction of pathways; (3) monitoring, development, and control of bioprocesses; (4) modification of their affinity and enzyme specificity (Abatenh et al. 2017).

Genetic engineering has allowed bacteria to be engineered which are capable of removing heavy metals such as Fe, As, Cu, Ni, Cd, and Hg (Verma and Singh 2005; D'Souza 2001; Azad et al. 2014; Ojuederie and Babalola 2017). Genes that have been indicated for use in genetically engineered microorganisms include the merA gene for the uptake of mercury, the phenol catabolic genes (pheA, pheB, pheC, pheD and pheR) (Marconi et al. 1997) and the ArsM gene for the removal of As from polluted soils (Liu et al. 2011).

Mercury is important but has been a challenge to remediate in different settings. *Pseudomonas* strains were engineered to become resistant to mercury by introducing of novel genes into the strain using plasmid pMR68 (Sone et al. 2013; Ojuederie and Babalola 2017). Genetically engineered *Pseudomonas putida* containing the merA gene and *Eschericia coli* strain M109 have been reported to effectively remove mercury from polluted soils and sediments (Chen and Wilson 1997; Barkay et al. 2003, Deckwer et al. 2004). Dixit et al. (2015) reported an instance in which the Mer operon from *Escherichia coli* coding for Hg^{2+} reduction was engineered genetically into the bacterium *Deinococcus geothemalis,* allowing it to abate mercury contamination at high temperatures.

One way to quickly and precisely determine the quantity of toxicants in a polluted site is the use of microbial biosensors that are developed using genetic engineering (Ojuederie and Babalola 2017) to estimate heavy metal concentrations such as Cu, Hg, As, Cd, and Ni in polluted sites (Dixit et al. 2015). The use of biosensors is however restricted due to variations in sensitivity, response time, threshold detection, stability, and length of signal relaxation (Kumar et al. 2013).

Challenges of Bioremediation

Genetically engineered microorganisms can achieve a high utilization or catalytic capacity with a small amount of cell mass, fast tracking the recovery of contaminated sites. However, the stability of the microbes must be maintained before their application in the field, since the stability of the recombinant plasmid introduced into the organism is primarily linked to the catabolic activity of a released GEM (Samanta et al. 2002; Ghosal et al. 2016). Otherwise, the death of cells occurs. Other drawbacks in the use of GEMs are that their release into the environment may be hazardous, substrate degradation and their growth can be delayed, and seasonal variations and other abiotic factor fluctuations can also have indirect and direct effects on microbial activity (Abatenh et al. 2017).

Considering the harsh environmental conditions in most sub-Saharan nations, the preservation of the recombinant bacterial population in the soil is very important. Only with suitable environmental conditions is the recombinant bacterial population able to withstand the antagonistic activity of indigenous bacterial populations (Dixit et al. 2015; Ojuederie and Babalola 2017).

Other challenges include:
Cost: The implementation of bioremediation can be costly, especially in the early stages. This includes the expenses of research, site assessment, organism cultivation, and monitoring. While bioremediation may be cost-effective in the long run compared to traditional methods, the upfront costs can be a barrier, particularly for developing countries or small-scale projects (Orellana et al. 2022; Kuppan et al. 2024). In some cases, bioremediation requires ongoing monitoring and maintenance to ensure effectiveness, which can add to the operational costs over time (Bala et al. 2022).
Scalability: Bioremediation is often site-specific, meaning it may not work equally well across different environmental conditions or types of contaminants (Alori et al. 2022). Scaling up bioremediation to address large, complex sites (e.g., polluted industrial zones or vast agricultural lands) can be challenging, especially when contaminants are widespread or deeply entrenched (Ashkanani et al. 2024) and bioremediation can take longer to achieve results compared to chemical or physical cleanup methods, which can limit its scalability in urgent situations or large-scale industrial applications (Azubuike et al. 2016).
Regulatory Limitations: Regulatory frameworks for bioremediation are often underdeveloped or inconsistent across regions. Without clear guidelines for the types of organisms that can be used, the methods of application, and acceptable contaminant reduction levels, regulatory uncertainty can hinder large-scale implementation (Shah et al. 2023).

Ethical and ecological considerations for using GMOs in remediation

The objective of genetic modification is to introduce desirable traits/features into the organisms so that their benefit can be used for various purposes such as in environmental clean-ups to break down toxic pollutants, such as removing heavy metals from contaminated soil (Rafeeq et al. 2023).

Ethical considerations include:
Biodiversity and Ecosystem Health: GMOs used in environmental remediation could potentially crossbreed with native species, leading to unintended genetic changes in local ecosystems. This could affect biodiversity, disrupt food chains, or lead to the loss of native species. Also, there may be concerns about "genetic pollution" where modified genes spread beyond the intended areas of remediation, potentially causing long-term ecological impacts (Aristidis et al. 2017).
Informed Consent and Public Opinion: Communities living in areas where GMOs are introduced may not be fully informed or may not consent to the use of GMOs in their environment. Public opinion and community values should be taken into account, and there should be transparency in decision-making (Sohi et al. 2023; Hassan et al. 2025).
Long-Term Consequences: The long-term impact of GMOs in environmental remediation is uncertain, and it is ethically important to consider potential unforeseen consequences. There may be ethical concerns regarding the irreversible changes GMOs could cause to natural ecosystems or human health. The precautionary principle suggests that we should avoid introducing new technologies until we have enough evidence to ensure they do not cause harm. This is particularly relevant when considering GMOs in ecological settings.

Ecological considerations include:
Impact on Non-target Species: GMOs used in environmental remediation may have unintended effects on non-target species. For instance, if genetically modified plants or microbes are used to detoxify pollutants, they could alter the habitat or food sources for other

organisms, potentially causing shifts in the local food web. Non-target species, such as pollinators, could be adversely affected if they interact with genetically modified organisms in unintended ways (Abdul Aziz et al. 2022).

Ecosystem Balance: Introducing GMOs could disrupt the natural balance of an ecosystem. For instance, if a genetically modified organism is more efficient at removing a pollutant, it might alter the dynamics of the surrounding environment, affecting plant growth, soil health, or water quality. The remediation process might inadvertently favour certain species over others, potentially leading to an imbalance in the ecosystem.

Resilience of Remediation Efforts: GMOs may offer effective short-term solutions for environmental remediation, but long-term ecological resilience is important. The stability of an ecosystem after remediation efforts are complete should be considered, as ecological systems can sometimes revert to their prior conditions or face new challenges in the absence of the modified organisms.

Soil and Microbial Health: GMOs used for soil remediation (such as genetically modified plants or microbes) might alter soil structure, microbial communities, and nutrient cycling. While some GMOs may improve soil health by detoxifying pollutants, others might harm soil biodiversity or microbial functions necessary for a healthy ecosystem.

Conclusions

This review paper focuses on the environmental problems caused by heavy metals contamination in sub-Saharan Africa and the effectiveness of microorganisms in restoring the contaminated environment through bioremediation. It highlights the different sources through which heavy metals enter the ecosystem, including natural processes which release heavy metals into the environment, including atmospheric emissions from volcanoes, the weathering of metal-enriched rocks and transport of continental dust in addition to artificial sources such as leaded gasoline, metal waste disposal, and the use paints, fertilizers, pesticides, animal manures, wastewater irrigation in agriculture, residues from coal combustion, petrochemical spillage, atmospheric deposition from different industrial sources and military training, among others. Bioaccumulation and biomagnification of heavy metals in the ecosystem has been documented, as has their harm to microorganisms, plants and humans, though more research is needed. Certain microorganism, both indigenous and genetically modified, have the ability to detoxify heavy metals to innocuous states. This is often a better option than physico-chemical treatment methods. The usage of genetically engineered microorganisms can greatly speed up the rate of bioremediation. Further utilization of this approach can be achieved by research harnessing our knowledge of proteomics and genomics, taking ethical and environmental concerns fully into account. Other novel molecular techniques for screening and isolating microbes for use in the bioremediation of heavy metals are needed.

AUTHOR CONTRIBUTIONS

IAA conceptualized the study, IAA, BSA, ZSO, and AMA participated in the search of databases, preparation and writing of the manuscript. All authors have read and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

TRANSPARENCY DECLARATION

The lead author affirms that this manuscript is an honest, accurate and transparent review of existing literatures

FUNDING
The authors received no funding for this work.

References

Abatenh, E., Gizaw, B., Tsegaye, Z. and Wassie, M. 2017. Application of microorganisms in bioremediation-review. *Journal of Environmental Microbiology*, 1(1):02-09.

Abbas, M., Parveen, Z., Iqbal, M., Riazuddin, M., Iqbal, S., Ahmed, M., and Bhutto, R. 2010. Monitoring of toxic metals (cadmium, lead, arsenic and mercury) in vegetables of Sindh, Pakistan. *Kathmandu University Journal of Science, Engineering and Technology*, 6(2):60–65. https://doi.org/10.3126/kuset.v6i2.4013

Abdul Aziz, M., Brini, F., Rouached, H and Masmoudi, K. 2022. Genetically engineered crops for sustainably enhanced food production systems. *Frontiers in Plant Science,* 8;13:1027828. doi: 10.3389/fpls.2022.1027828.

Abii, T.A. 2012. Levels of Heavy Metals (Cr, Pb, Cd) Available for plants within abandoned mechanic workshops in Umuahia Metropolis *Research Journal of Chemical Sciences*, 2(2):79-82.

Abrahams P.W. 2002. Soils: their implications to human health. *Science of the Total Environment*, 291(1–3):1–32. doi: 10.1016/s0048-9697(01)01102-0.

Adeniyi A.A. 1996. Determination of cadmium, copper, iron, lead manganese and zinc in water leaf (*Talinum triangulae*) in dumpsites. *Environmental International*, 22:259-262. https://doi.org/10.1016/0160-4120(96)00011-6

Ahmad M.S. and Ashraf M. 2011. Essential roles and hazardous effects of nickel in plants. *Reviews of Environmental Contamination and Toxicology*, 214:125–167. doi: 10.1007/978-1-4614-0668-6_6.

Ajaz haja mohideena, R., Thirumalai Arasuc, V., Narayananb, K.R. and Zahir Hussaind, M.I. 2010. Bioremediation of Heavy metal contaminated soil by the Exigobacterium and accumulation of Cd, Ni, Zn and Cu from Soil environment. *International Journal of Biological Technology*, 1(2):94-101.

Alengebawy, A., Abdelkhalek, S.T., Qureshi, S. R. and Wang, M.Q. 2021. Heavy metals and pesticides toxicity in agricultural soil and plants: ecological risks and human health implications. *Toxics*, 9:42. https://doi.org/10.3390/toxics9030042

Ali, W., Ma, Y., Zhu, J., Zou, H. and Liu Z. 2022. Mechanisms of cadmium-induced testicular injury: a risk to male fertility. *Cells*, 11(22):3601. doi: 10.3390/cells11223601.

Aljohani, A.S.M. 2023. Heavy metal toxicity in poultry: a comprehensive review. *Frontiers in Veterinary Science*, 10:1161354. doi: 10.3389/fvets.2023.1161354.

Al-Jassir, M.S., Shaker, A. and Khaliq, M.A. 2005. Deposition of Heavy Metals on Green Leafy Vegetables Sold on Roadsides of Riyadh City, Saudi Arabia. *Bulletin of Environmental Contamination and Toxicology*, 75:1020-1027. http://dx.doi.org/10.1007/s00128-005-0851-4

Alloway, B.J. 1995. Heavy Metals in Soils. Blackie Academic and Professional, Chapman and Hall: London, 368p. https://doi.org/10.1007/978-94-011-1344-1

Alloway, B. J. 2013. Sources of heavy metals and metalloids in soils. In: B. J. Alloway (Ed.), Heavy Metals in Soils. Dordrecht: Springer. (pp. 11-50). https://doi.org/10.1007/978-94-007-4470-7

Alori, E. T., Gabasawa, A. I., Elenwo, C. E., and Agbeyegbe, O. O. 2022. Bioremediation techniques as affected by limiting factors in soil environment. *Frontiers in Soil Science*, *2*. https://www.frontiersin.org/journals/soil-science/articles/10.3389/fsoil.2022.937186

Angon, P.B., Islam, M.S., Shreejana, K.C. Das, A., Anjum, N., Poudel, A. and Suchi, S.A. 2024. Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*. doi.org/10.1016/j.heliyon.2024.e28357.

Anuoluwa, I.A., Oyinloye, B.E., Ogunmola, O.P. 2021. Heavy metals contamination of arable lands: a threat to food security and safety. In: Babalola, O.O. (eds.) Food Security and Safety. Springer, Cham. https://doi.org/10.1007/978-3-030-50672-8_39

Aristidis, T., Nawaz, M.A., Kouretas, D., Balias, G., Savolainen, K., Tutelyan, V.A., Golokhvast, K.S., Lee, J.D., Yang, S.H. and Chung, G. 2017. Environmental impacts of genetically modified plants: A review. *Environmental Research*, 157:818–833. 10.1016/j.envres.2017.03.011.

Ashkanani, Z., Mohtar, R., Al-Enezi, S., Smith, P. K., Calabrese, S., Ma, X., and Abdullah, M. 2024. AI-assisted systematic review on remediation of contaminated soils with PAHs and heavy metals. *Journal of Hazardous Materials*, *468*:133813. https://doi.org/https://doi.org/10.1016/j.jhazmat.2024.133813

Azad, M.A.K., Amin, L. and Sidik, N.M. 2014. Genetically engineered organisms for bioremediation of pollutants in contaminated sites. *Chinese Science Bulletin*, 59:703–714. doi:10.1007/s11434-013-0058-8

Aziz, K. H. H., Mustafa, F. S., Omer, K. M., Hama, S., Hamarawf, R. F., and Rahman, K. O. 2023. Heavy metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their toxicity: a review. *RSC Advances*, 13(26):17595–17610. https://doi.org/10.1039/D3RA00723E

Azubuike, C. C., Chikere, C. B., and Okpokwasili, G. C. 2016. Bioremediation techniques-classification based on site of application: principles, advantages, limitations and prospects. *World Journal of Microbiology and Biotechnology*, 32(11):180. https://doi.org/10.1007/s11274-016-2137-x

Bååth, E.; Frostegård, Å.; Montserrat, D.R. and Tunlid, A. 1998a. Bacterial community-based measurements to estimate heavy metal effects in soil. The use of phospholipid fatty acid patterns and bacterial community tolerance. *Ambio*, 27:58-61. https://www.jstor.org/stable/4314686

Bååth, E.; Diaz-Ravina, M.; Frostegård, A. and Campbell, C.D. 1998b. Effect of metal-rich sludge amendments on the soil bacterial community. *Applied Environmental Microbiology*, 64:238-245. https://doi.org/10.1128/AEM.64.1.238-245

Badawy S.H. and EL-Motaium R.A. 2003. Fate of some heavy metals in sandy soil amended with sewage sludge and their accumulation in plants. *Egypt Journal of Environmental Science*, 43(1):1-17.

Bakidere S. and Yaman M. 2008. Determination of lead, cadmium and copper in road-side soil and plants in Elazig Turkey. *Environmental Monitoring and Assessment*, 136:401-410. doi: 10.1007/s10661-007-9695-1.

Bala, S., Garg, D., Thirumalesh, B.V., Sharma, M., Sridhar, K., Inbaraj, B.S. and Tripathi, M. 2022. Recent strategies for bioremediation of emerging pollutants: a review for a green and sustainable environment. *Toxics*, 10:484. https://doi.org/10.3390/toxics10080484

Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M.R and Sadeghi, M. 2021. Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology*, 12:643972. doi: 10.3389/fphar.2021.643972.

Bamforth S.M. and Singleton I. 2005. Bioremediation of polycyclic aromatic hydrocarbons: current knowledge and future directions. *Journal of Chemical Technology and Biotechnology*, 80:723–736. https://doi.org/10.1002/jctb.1276

Barba-Gutiérrez, Y., Adenso-Díaz, B. and Hopp, M. 2008. An analysis of some environmental consequences of European electrical and electronic waste regulation. *Resources, Conservation* and *Recycling*, 3(52):481–495. https://doi.org/10.1016/j.resconrec.2007.06.002

Barkay, T., Miller, S.M. and Summers, A.O. 2003. Bacterial mercury resistance from atoms to ecosystems. *FEMS Microbiol. Rev.*, 27:355–384. doi: 10.1016/S0168-6445(03)00046-9.

Bharti, K.R and Sharma, R. 2021. Effect of heavy metals: An overview. *Materials Today: Proceedings*, 51(Part 1):880-885. https://doi.org/10.1016/j.matpr.2021.06.278

Brevik E.C. 2013. Soils and human health: An overview. *In:* E.C. Brevik and L.C. Burgess, eds. *Soils and Human Health*, pp. 29–58. https://doi.org/10.1201/b13683

Bruins, M.R., Kapil, S. and Oehme, F.W. 2000. Microbial resistance to metals in the environment. *Ecotoxicology and Environmental Safety*, 45:198-207. https://doi.org/10.1006/eesa.1999.1860

Brzóska M.M. and Moniuszko-Jakoniuk J. 2005. Disorders in bone metabolism of female rats chronically exposed to cadmium. *Toxicology and Applied Pharmacology,*202(1):68–83. https://doi.org/10.1016/j.taap.2004.06.007

Buermans, H. and Den Dunnen, J. 2014. Next generation sequencing technology: Advances and applications. *Biochimica et Biophysica Acta*, 1842:1932–1941. https://doi.org/10.1016/j.bbadis.2014.06.015

Burgess LC. 2013. Organic pollutants in soil. *Soils and Human Health*, pp. 83–106. Boca Raton, Fla: CRC Press.

Buta, M., Hubeny, J., Zieliński, W., Harnisz, M. and Korzeniewska, E. 2021. Sewage sludge in agriculture – the effects of selected chemical pollutants and emerging genetic determinants on the quality of soil and crops – a review. *Ecotoxicology and Environmental Safety*, 214:112070. https://doi.org/10.1016/j.ecoenv.2021.112070

Cachada, A., Rocha-Santos, T., and Duarte, A.C. 2018. Chapter 1 - Soil and pollution: an introduction to the main issues. IN: *Soil Pollution*, Academic Press, pp. 1–28. https://doi.org/10.1016/B978-0-12-849873-6.00001-7

Camargo, F.A., Okeke, B.C., Bento, F.M. and Frankenberger, W.T. 2003. In vitro reduction of hexavalent chromium by a cell-free extract of *Bacillus* sp. ES 29 stimulated by Cu^{2+}. *Applied Microbiology and Biotechnology*, 62(5-6):569-573. https://doi.org/10.1007/s00253-003-1291-x

Cang, L., Wang, Y., Zhou, D. and Dong, Y. 2004. Heavy metals pollution in poultry and livestock feeds and manures under intensive farming in Jiangsu Province, China. *Journal of Environmental Sciences (China)*, 16(3):371–374.

Chen, C. and Wang, J.L. 2007. Characteristics of Zn^{2+} biosorption by *Saccharomyces cerevisiae. Biomedical and Environmental Sciences*, 20:478–482.

Chen S. and Wilson D.B. 1997. Genetic engineering of bacteria and their potential for Hg^{2+} bioremediation. *Biodegradation,* 8:97–103. https://doi.org/10.1023/a:1008233704719

Chen, Y., Li, X. and Shen, Z. 2004. Leaching and uptake of heavy metals by ten different species of plants during an EDTA-assisted phytoextraction process. *Chemosphere*, 57(3): 187–196. https://doi.org/10.1016/j.chemosphere.2004.05.044

Chen, Y.X., Wang, Y.P.; Lin, Q. and Luo, Y.M. 2005. Effect of copper-tolerant rhizosphere bacteria on mobility of copper in soil and copper accumulation by *Elsholtzia splendens. Environment International*, 31:861-866. https://doi.org/10.1016/j.envint.2005.05.044

Chen, B. and Dong, S. 2022. Mercury contamination in fish and its effects on the health of pregnantwomen and their fetuses, and guidance for fish consumption—a narrativ review. *International Journal of Environmental Research and Public Health*, 19:15929. https://doi.org/10.3390/ijerph192315929

Chu, D. 2018. Effects of heavy metals on soil microbial community. *IOP Conference Series: Earth and Environmental Science*, 113:012009. doi: 10.1088/1755-1315/113/1/012009

Cui, Y.L., Zhu, Y.G., Zhai, R.H., Chen, D.Y., Huang, Y.Z., Qiu, Y., and Liang, J.Z. 2004. Transfer of metals from soil to vegetables in an area near a smelter in Nanning, China. *Environmental International*, 30:785-791. https://doi.org/10.1016/j.envint.2004.01.003

D'souza, S.F. 2001. Microbial biosensors. *Biosensors and Bioelectronics*, 16:337–353. https://doi.org/10.1016/S0956-5663(01)00125-7

Dahlin, S., Witter, E., Mårtensson, A., Turner, A. and Bååth, E. 1997. Where´s the limit? Changes in the microbiological properties of agricultural soils at low levels of metal contamination. *Soil Biology and Biochemistry*, 29:1405-1415. https://doi.org/10.1016/S0038-0717(97)00048-5

Das, S., Sultana, K.W., Ndhlala, A.R., Mondal, M. and Chandra, I. 2023. Heavy metal pollution in the environment and its impact on health: exploring green technology for remediation. *Environmental Health Insights*, 17:11786302231201259. doi: 10.1177/11786302231201259.

Deckwer, W.D., Becker, F., Ledakowicz, S. and Wagner-Döbler, I. 2004. Microbial removal of ionic mercury in a three-phase fluidized bed reactor. *Environmental Science and Technology*, 38(6):1858–1865. https://doi.org/10.1021/es0300517

Diaz, E. 2004. Bacterial degradation of aromatic contaminants: a paradigm of metabolic versatility. *International Microbiology*, 7:173–180.

Dinev, N. and Bojinova, P. 2006. Ecological investigations and agricultural status in the region of lead-zinc smelter near the town of Plovdiv. Proceedings of First International Symposium "Ecological approaches towards the production of safety food", 19-20 Oct. 2006, Assoc "Regional science and Technology Unions"-Plovdiv, Bulgaria, pp. 121-126.

Dinev, N. and Vassilev, A. 2006. Phytoremediation and sustainable use of metal contaminated soil in Bulgaria. In: Processing of IMIDRA- Soil Remediation Technologies, November, Madrid.

Di Toppi, L.S., Lambardi, M., Pazzagli, L., Cappugi, G., Durante, M. and Gabbrielli, R.1999. Response to cadmium in carrot *in vitro* plants and cell suspension cultures. *Plant Science*, 137:119–129.

Dixit, R., Wasiullah, Malaviya, D., Pandiyan, K., Singh, U.B., Sahu, A., Shukla, R., Singh, B.P., Rai, J.P., Sharma, P.K., Lade, H. and Paul, D. 2015. Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. *Sustainability*, 7(2):2189-2212. https://doi.org/10.3390/su7022189

Dragan, F., Lestyan, M., Lupu, V.V., Marcu, F.M., Cozma, A., Fodor, K., Ciubara, A., Moisa, C.F., Teaha, D., Lupu, A., Starcea, I.M., Ignat, A.E. and Ciubara, A.B. 2023. The threat of mercury poisoning by fish consumption. *Applied Sciences*, 13:369. https://doi.org/10.3390/app13010369

Dudka S. and Adriano D.C. 1997. Environmental impacts of metal ore mining and processing: A review. *Journal of Environmental Quality*, 26:590–602. https://doi.org/10.2134/jeq1997.00472425002600030003x

Dudka S, and Miller WP. 1999. Accumulation of potentially toxic elements in plants and their transfer to human food chain. *Journal of Environmental Science and Health. Part. B, Pesticides, Food Contaminants, and Agricultural Wastes*, 34:681–708.

https://doi.org/10.1080/03601239909373221

Duruibe, J.O., Ogwuegbu, M.O.C. and Egwurugwu, J.N. 2007. Heavy metal pollution and human biotoxic effects. *International Journal of Physical Sciences*, 2(5):112-118.

Eddy, N.O. 2004. Physicochemical parameter of water and heavy metal content of water, sediment and fishes from Qua Iboe River Estuary. M.Sc Thesis. Michael. Okpara University of Agriculture, Umudike, Nigeria

Ernst, W.H.O. 1998. *The origin and ecology of contaminated, stabilized and non-pristine soils*. In: Vangronsveld, J. and Cunningham, S.D. (Eds). Metal-contaminated Soil. (Chapter 2). New York: Springer, pp. 17-29.

Erdogan, S., Onal, Y., Akmil-Basar. C., Bilmez-Erdemoglu, S.C., Sarici-ozdemir, C., Koseoglu, E. and Leduygu, G. 2005. Optimization of nickel adsorption from aqueous solution by using activated carbon prepared from waste apricot by chemical activation. *Applied Surface Science*, 252:1324-1331. https://doi:10.1016/j.apsusc.2005.02.089

Evanko C.R. and Dzombak D.A. 1997. Remediation of metals-contaminated soil and groundwater. *Environmental Science*, 412:1-45.

Fasinu P.S., and Orisakwe O.E. 2013. Heavy metal pollution in Sub-Saharan Africa and possible implications in cancer epidemiology, *Asian Pacific Journal of Cancer Prevention*, *14*. http://dx.doi.org/10.7314/APJCP.2013.14.6.3393

Fergusson J.E. 1990. The Heavy Elements; Chemistry of Environmental Impact and Health Effects. Pergamon Press, England, pp. 20-35.

Ferhan, M., Ahmed, Z., Riazuddin, S., Rajoka, M.I. and Khalid, A.M. 2002. Estimation and removal of phenol in pharmaceutical industrial effluents from paracetamol and aspirin manufacturing units. *OnLine Journal of Biological Sciences*, 2:587–590. https://doi.org/10.3923/jbs.2002.587.590

Fliessbach, A., Martens, R. and Reber, H.H. 1994. Soil bacterial biomass and bacterial activity in soil treated with heavy metal contaminated sewage sludge. *Soil Biology and Biochemistry*, 26:1201- 1205. https://doi.org/10.1016/0038-0717(94)90144-9

Frostegård, Å., Tunlid, A. and Bååth, E. 1993. Phospholipid fatty acid composition, biomass, and activity of bacterial communities from two soil types experimentally exposed to different heavy metals. *Applied Environmental Microbiology*, 11:3605-3617. https://doi.org/10.1128/aem.59.11.3605-3617.1993

Fulekar, M.H. 2010. Bioremediation technology for hazardous wastes - recent advances. In: Fulekar, M.H. (ed.) Bioremediation Technology. Dordrecht: Springer. https://doi.org/10.1007/978-90-481-3678-0_5

Gadd, G.M. 2000. Bioremedial potential of bacterial mechanisms of metal mobilization and immobilization. *Current Opinion in Biotechnology*, 11:271–279. https://doi.org/10.1016/s0958-1669(00)00095-1

Garbisu C. and Alkorta I. 1997. Bioremediation: Principles and future. *Journal of Clean Technology, Environmental Toxicology and Occupational Medicine*, 6:1-16.

Gavrilescu, M. 2004. Removal of heavy metals from the environment by biosorption. *Engineering in Life Sciences*, *4*(3):219-232. https://doi.org/10.1002/elsc.200420026

Ghosal, D., Ghosh, S., Dutta, T.K. and Ahn, Y. 2016. Current state of knowledge in microbial degradation of polycyclic aromatic hydrocarbons (PAHS): A review. *Frontiers in Microbiology*, 7:1369. https://doi.org/10.3389/fmicb.2016.01369

Gilis, A., Khan, M.A., Cornelis, P., Meyer, J.M., Mergeay, M. and van der Lelie, D. 1996. Siderophore-mediated iron uptake in *Alcaligenes eutrophus* CH34 and identification of *ale*B encoding ferric-alcaligin E receptor. *Journal of Bacteriology*, 178(18):5499-5507. https://doi.org/10.1128/jb.178.18.5499-5507.1996

Gottesfeld, P., Were, F.H., Adogame, L., Gharbi, S., San, D., Nota, M.M. and Kuepouo, G.

2018. Soil contamination from lead battery manufacturing and recyling in seven African countries. *Environmental Research*, 161:609–614. https://doi.org/10.1016/j.envres.2017.11.055

Greenwood N.N., and Earnshaw A. 1993. *Chemistry of the Elements*. New York: Pergamon Press. pp. 404-405.

Guerra, F., Trevizam, A.R., Muraoka, T., Marcante, N.C. and Canniatti-Brazaca, S.G. 2012. Heavy metals in vegetables and potential risk for human health. *Scientia Agricola*, 69(1):54–60. https://doi.org/10.1590/S0103-90162012000100008

Guha, H., Jayachandran, K. and Maurrasse, F. 2001. Kinetics of chromium (VI) reduction by a type strain *Shewanella alga* under different growth conditions. *Environmental Pollution*, 115:209–218. https://doi.org/10.1016/S0269-7491(01)00108-7

Haider, F. U., Cai, L., Coulter, J. A., Cheema, S. A., Wu, J., Zhang, R., Ma, W., and Farooq, M. 2021. Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicology and Environmental Safety*, 211:111887. https://doi.org/10.1016/j.ecoenv.2020.111887

Hassan, H.F., Yassine, H., Chaaban, A., Chehaitly, A., Skaineh, Z., Cherri, N., Moussawi, S., Baytarmouni, N., Kobeissy, P.H., Dimassi, H and Ibrahim, J.N. 2025. Public knowledge, attitudes, and perceptions toward genetically modified foods in Lebanon. *GM Crops and Food*, 16(1):144–155. https://doi.org/10.1080/21645698.2025.2450852

Höfte, M., Dong, Q., Kourambos, S., Krishnapillai, V., Sherratt, D. and Mergeay, M. 1994. The *sss* gene product, which affects pyoverdin production in *Pseudomonas aeruginosa* 7NSK2, is a site-specific recombinase. *Molecular Microbiology,* 14:1011-1020.

Hough, R.L., Young, S.D. and Crout, N.M.G. 2003. Modeling of Cd, Cu, Ni, Pb and Zn uptake by winter wheat and forage maize, from a sewage disposal form. *Soil Use and Management*, 19:19-27. doi:10.1079/sum2002157

Hu, X., Wang, J., Liu, Y., Liu, X., Zhong, J., Cui, X., Zhang, M., Ma, D., Xiao, Y., and Zhu, X. 2021. Effects of Heavy Metals/Metalloids and soil properties on microbial communities in farmland in the vicinity of a metals smelter. *Frontiers in Microbiology*, 12. https://doi.org/10.3389/fmicb.2021.707786

Huang, D., Xu, Q., Cheng, J., Lu, X. and Zhang, H. 2012. Electrokinetic remediation and its combined technologies for removal of organic pollutants from contaminated soils. *International Journal of Electrochemical Science*, 7:4528-4544. https://doi.org/10.1016/S1452-3981(23)19558-7

Hussein, H., Krull, R., Abou El-Ela, S.I. and Hempel, D.C. 2001. *Interaction of the different heavy metal ions with immobilized bacterial culture degrading xenobiotic wastewater compounds.* In Proceedings of the Second International Water Association World Water Conference, Berlin, Germany, 15–19 October; pp. 15–19.

Igiri, B., Okoduwa, S. I. R., Idoko, G. O., Akabuogu, E. P., Adeyi, A., and Ejiogu, I. K. 2018. Toxicity and Bioremediation of Heavy Metals Contaminated Ecosystem from Tannery Wastewater: A Review. *Journal of Toxicology*, 2568038:1–16. https://doi.org/10.1155/2018/2568038

Ikhimalo, O. P. and Ugbenyen, A. M. 2023. Utilization of mushroom for the bioremediation of plastics and polyethenes. *Syncytia*, 1(1), 16-26. doi: 10.52679/syncytia.

Infante, J.C., De Arco, R.D. and Angulo, M.E. 2014. Removal of lead, mercury and nickel using the yeast *Saccharomyces cerevisiae. Revista MVZ Córdoba*, 19:4141-4149. http://dx.doi.org/10.21897/rmvz.107

Iram, S, Ahmad, I. and Stuben, D. 2009. Analysis of mines and contaminated agricultural soil samples for fungal diversity and tolerance to heavy metals. *Pakistan Journal of Botany*, 41(2):885-895.

Itai, T., Otsuka, M., Asante, K.A., Muto, M., Opoku-Ankomah, Y., Ansa-Asare, O.D. and Tanabe, S. 2014. Variation and distribution of metals and metalloids in soil/ash mixtures from Agbogbloshie e-waste recycling site in Accra, Ghana. *The Science of the Total Environment*, 470–471:707–716. https://doi.org/10.1016/j.scitotenv.2013.10.037

Iwamoto, T. and Nasu, M. 2001. Current bioremediation practice and perspective. *Journal of Bioscience and Bioengineering*, 92(1):1-8. https://doi.org/10.1016/S1389-1723(01)80190-0

Iyengar, V. and Nair, P. 2000. Global outlook on nutrition and the environment: meeting the challenges of the next millennium. *Science of the Total Environment*, 249:331-346. https://doi.org/10.1016/s0048-9697(99)00529-x

Jain P.K., Gupta V.K., Bajpai V., Lowry M. and Jaroli D.P. 2011. GMO's: Perspective of bioremediation. In: Recent Advances in Environmental Biotechnology, Jain P.K., Gupta, V.K. and Bajpai V. (Eds.). LAP Lambert Academic Publishing AG and Co. KG, Germany, pp 6-23.

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B. and Beeregowda, K.N. 2014. Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, 7(2). https://doi.org/10.2478/intox-2014-0009

Japenga, J., Bonten, L., Kucharski, R., Novosielska, O. and Dinev, N. 2005. Revegetation as a tool for risk containment of heavy metal polluted sites. Third International Phytotechnologies Conference. April 20-22, Atlanta, GA.

Jarup L. 2003. Hazards of heavy metals contamination. *British Medical Bulletin*, 68:167-182. https://doi.org/10.1093/bmb/ldg032

Ji, G. and Silver, S. 1995. Bacterial resistance mechanisms for heavy metals of environmental concern. *Journal of Industrial Microbiology*, 14:61-75. https://doi.org/10.1007/BF01569887

Jomova, K., Makova, M., Alomar, S.Y., Alwasel, S.H., Nepovimova, E., Kuca, K., Rhodes, C.J. and Valko, M. 2022. Essential metals in health and disease Klaudia *Chemico-Biological Interactions* 367(2022):110173. https://doi.org/10.1016/j.cbi.2022.110173

Jordão, C.P., Nascentes, C.C., Cecon, P.R., Fontes, R.L.F. and Pereira, J.L. 2006. Heavy metal availability in soil amended with composted urban solid wastes. *Environmental Monitoring and Assessment*, 112(1–3):309–326. https://doi.org/10.1007/s10661-006-1072-y

Kabata-Pendias, A. and Mukherjee A.B. 2007. Trace elements from soil to human. New York: Springer-Verlag. http://dx.doi.org/10.1007/978-3-540-32714-1

Kachenko, A.G. and Singh, B. 2006. Heavy metals contamination in vegetables grown in urban and metal smelter contaminated sites in Australia. *Water, Air and Soil Pollution*, 169:101-123. doi.org/10.1007/s11270-006-2027-1

Kashem, M.A. and Singh, B.R. 2004. Transformation in solid phase species of metals as affected by flooding and organic matter additions in contaminated soils. *Communications in Soil, Science and Plant Analysis*, 35:1435-1456. http://dx.doi.org/10.1081/CSS-120037556

Kaufman, J.A., Brown, M.J., Umar-Tsafe,N.T., Adbullahi, M.B., Getso, K.I., Kaita, I.M., Sule, B.B., Ba'aba, A., Davis, L., Nguku, P.M. and Sani-Gwarzo, N. 2016. Prevalence and Risk Factors of Elevated Blood Lead in Children in Gold Ore Processing Communities, Zamfara, Nigeria, 2012. *Journal of Health* and *Pollution*, 6(11):1-8. doi: 10.5696/2156-9614-6-11.2.

Kuppan, N., Padman, M., Mahadeva, M., Srinivasan, S., and Devarajan, R. 2024. A comprehensive review of sustainable bioremediation techniques: Eco friendly solutions for waste and pollution management. *Waste Management Bulletin*, *2*(3):154–171. https://doi.org/https://doi.org/10.1016/j.wmb.2024.07.005

Khan, M. and Scullion, J. 2000. Effect of soil on bacterial responses to metal contamination. *Environmental Pollution*, 110:115-125. https://doi.org/10.1016/S0269-7491(99)00288-2

Khan, M.S., Shil, N.C. and Noor, S. 2008. Integrated nutrient management for sustainable yield of major vegetable crops in Bangladesh. *Bangladesh Journal of Agriculture and Environment*, 4:81-94.

Kkairiah, J., Zalifah, M.K., Yin, Y.H. and Aminah, A. 2004. The uptake of heavy metals by fruit type vegetables grown in selected agricultural areas. *Pakistan Journal of Biological Sciences*, 7:1438-1442. https://doi.org/10.3923/pjbs.2004.1438.1442

Knox, A.S., Seamans, J.C., Mench, M.J. and Vangronseveld, J. 2000. *Remediation of metals and Radionuclides*. Contaminated Soil Using In Situ Stabilization Techniques. New York: Macmillan Publishers, pp. 21-26. http://dx.doi.org/10.1201/9781420026269.ch2

Konopka, A., Zakharova, T., Bischoff, M., Oliver, L., Nakatsu, C. and Turco, R.F. 1999. Bacterial biomass and activity in lead-contaminated soil. *Applied Environmental Microbiology*, 65:2256-2259. https://doi.org/10.1128/aem.65.5.2256-2259.1999

Kozlowski, C.A. and Walkowrak, W. 2002. Removal of Cr^{6+} from aqueous solutions by polymer inclusion membranes. *Water Research*, 36:4870-4876. https://doi.org/10.1016/s0043-1354(02)00216-6

Kumar, A. and Maiti, S.K. 2015. Assessment of potentially toxic heavy metal contamination in agricultural fields, sediment, and water from an abandoned chromite-asbestos mine waste of Roro hill, Chaibasa, India. *Environmental Earth Sciences*, 74(3):2617–2633. https://doi.org/10.1007/s12665-015-4282-1

Kumar, S., Dagar, V.K., Khasa, Y.P. and Kuhad, R.C. 2013. Genetically modified microorganisms (GMOS) for bioremediation. In: Kuhad, R., Singh, A., Eds., Biotechnology for Environmental Management and Resource Recovery. New Delhi: Springer, pp. 191–218. https://doi.org/10.1007/978-81-322-0876-1_11

Le Faucheur, S., Schildknecht, F., Behra, R. and Sigg, L. 2006. Thiols in *Scenedesmus vacuolatus* upon exposure to metals and metalloids. *Aquatic Toxicology*, 80:355–61. https://doi.org/10.1016/j.aquatox.2006.10.002

Lei, Y., Guo, M., Xie, J., Liu, X., Li, X., Wang, H., Xu, Y. and Zheng, D. 2024. Relationship between blood cadmium levels and bone mineral density in adults: a cross-sectional study. *Frontiers in Endocrinology*, 15:1354577. doi: 10.3389/fendo.2024.1354577.

Lim, P.E., Mak, K.Y., Mohamed, N. and Noor, A.M. 2003. Removal and speciation of heavy metals along the treatment path of wastewater in subsurface-flow constructed wetlands. *Water Science and Technology*, 48:307–313.

Lin, C.C. and Lin, H.L. 2005. Remediation of soil contaminated with the heavy metal (Cd^{2+}). *Journal of Hazardous Materials*, 122:7–15. https://doi.org/10.1016/j.jhazmat.2005.02.017

Liu, S., Zhang, F., Chen, J. and Sun, G. 2011. Arsenic removal from contaminated soil via biovolatilization by genetically engineered bacteria under laboratory conditions. *Journal of Environmental Sciences*, 23:1544–1550. https://doi.org/10.1016/S1001-0742(10)60570-0

Lovley, D.R 1993. Dissimilatory metal reduction. *Annual Review of Microbiology*, 47:263-290. https://doi.org/10.1146/annurev.mi.47.100193.001403

Lu, Y., Song, S., Wang, R., Liu, Z., Meng, J., Sweetman, A.J., Jenkins, A., Ferrier, R.C., Li, H., Luo, W. and Wang, T. 2015. Impacts of soil and water pollution on food safety and health risks in China. *Environment International*, 77:5–15. https://doi.org/10.1016/j.envint.2014.12.010

Mackay, A.K., Taylor, M.P., Munksgaard, N.C., Hudson-Edwards, K.A. and Burn-Nunes, L.2013. Identification of environmental lead sources and pathways in a mining and smelting town: Mount Isa, Australia. *Environmental Pollution*, 180:304–311. https://doi.org/10.1016/j.envpol.2013.05.007

Malik, A. 2004. Metal bioremediation through growing cells. *Environment International*, 30:261–278. https://doi.org/10.1016/j.envint.2003.08.001

Mani, D. and Kumar, C. 2014. Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: An overview with special reference to phytoremediation. *International Journal of Environmental Science and Technology*, 11:843–872. https://doi.org/10.1007/s13762-013-0299-8

Marconi, A.M.; Kieboom, J. and de Bont, J.A. 1997. Improving the catabolic functions in the toluene-resistant strain *Pseudomonas putida* 12. *Biotechnology Letters*, 19:603–606. https://doi.org/10.1023/A:1018366126573

Marshall, 2004. Enhancing food chain integrity: Quality assurance mechanism for air pollution impacts on fruits and vegetables systems. Crop Post Harvest Program, Final Technical Report (R7530).

Masindi, V., and Muedi, K. L. 2018. Environmental contamination by heavy metals. In Heavy Metals (pp. 115-133). IntechOpen. https://doi.org/10.5772/intechopen.76082

Massachusetts Department of Environmental Protection Publication (MADEP) 1993. 310 CMR 40.0000: Massachusetts Contingency Plan (MCP). Boston.

Meena, A.K., Mishra, G.K., Rai, P.K., Rajgoapal, C. and Nagar, P.N. 2005. Removal of heavy metal ions from aqueous solutions using carbon aerogel as an adsorbent. *Journal of Hazardous Materials*, 122:161-170. https://doi.org/10.1016/j.jhazmat.2005.03.024

Mileusnić, M., Mapani, B.S., Kamona, A.F., Ružičić, S., Mapaure, I. and Chimwamurombe, P.M. 2014. Assessment of agricultural soil contamination by potentially toxic metals dispersed from improperly disposed tailings, Kombat mine, Namibia. *Journal of Geochemical Exploration*, 144:409–420. https://doi.org/10.1016/j.gexplo.2014.01.009

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

Mushtaq, N. and Khan, K.S. 2010. Heavy metals contamination of soils in response to wastewater irrigation in Rawalpindi Region. *Pakistan Journal of Agricultural Sciences*, 47(3):215-224.

Najeeb, U., Ahmad, W., Zia, M.H., Zaffar, M. and Zhou, W. 2017. Enhancing the lead phytostabilization in wetland plant Juncus effusus L. through somaclonal manipulation and EDTA enrichment. *Arabian Journal of Chemistry*, 10:S3310–S3317. https://doi.org/10.1016/j.arabjc.2014.01.009

Natural and Accelerated Bioremediation Research (NABIR) Program, Office of Biological and Environmental Research, Office of Science, U.S. Department of Energy. 2003. *What is bioremediation*? p. 9.

National Research Council (NRC) 1993. *In situ Bioremediation. When does it work?* Washington DC: National Academy Press., pg. 13.

Navarro, M.C., Pérez-Sirvent, C., Martínez-Sánchez, M.J., Vidal, J., Tovar, P.J. and Bech, J. 2008. Abandoned mine sites as a source of contamination by heavy metals: A case study in a semi-arid zone. *Journal of Geochemical Exploration*, 96(2–3):183–193.

https://doi.org/10.1016/j.gexplo.2007.04.011

Nicholson, F.A., Smith, S.R., Alloway, B.J., Carlton-Smith, C. and Chambers. B.J. 2003. An inventory of heavy metals inputs to agricultural soils in England and Wales. *The Science of the Total Environment*, 311:205–219. https://doi.org/10.1016/S0048-9697(03)00139-6

Nicoli, M.C., Anese, M. and Parpinel, M. 1999. Influence of processing on the antioxidant properties of fruit and vegetables. *Trends in Food Science and Technology*, 10:94-100. https://doi.org/10.1016/S0924-2244(99)00023-0

Nies, D.H. and Silver, S. 1995. Ion efflux systems involved in bacterial metal resistances. *Journal of Industrial Microbiology*, 14:186-199. https://doi.org/10.1007/BF01569902

Nies, D.H. 1999. Bacterial heavy-metal resistance. *Applied Microbiology and Biotechnology*, 51:730-750. http://dx.doi.org/10.1007/s002530051457

Oberg, M., Jaakkola, M.S., Woodward, A. and Peruga A, Prüss-Ustün A. 2011. Worldwide burden of disease from exposure to second-hand smoke: a retrospective analysis of data from 192 countries. *Lancet*, 377:139-46. https://doi.org/10.1016/S0140-6736(10)61388-8

Odoh, R. and Kolawole, S.A. 2011. Assessment of trace heavy metal contaminations of some selected vegetables irrigated with water from River Benue within Makurdi Metropolis, Benue State Nigeria. *Advances in Applied Science Research*, 2(5):590-601.

Ogbeide, O. and Henry, B. 2024. Addressing Heavy Metal Pollution in Nigeria: Evaluating Policies, Assessing Impacts, and Enhancing Remediation Strategies. *Journal of Applied Science and Environmental Management*, *28*(4):1007-1051. https://doi.org/10.4314/jasem.v28i4.5

Ogundele, L.T.; Owoade, O.K.; Hopke, P.K. and Olise, F.S. 2017. Heavy metals in industrially emitted particulate matter in Ile-Ife, Nigeria. *Environmental Research*, 156:320–325. https://doi.org/10.1016/j.envres.2017.03.051

Ojuederie, O.B. and Babalola, O.O. 2017. Microbial and Plant-Assisted Bioremediation of Heavy Metal Polluted Environments: A Review. *International Journal of Environmental Research and Public Health*, 14:1504. doi: 10.3390/ijerph14121504.

Oke, J.M. and Hamburger, M.O. 2002. Screening of some Nigerian medicinal plants for antioxidant activity using 2, 2-diphenyl-picryl-hydrazyl radical. *African Journal of Biomedical Research*, 5:77-79.

Omotehinse, A.O. and Ako, B. D. 2019. The environmental implications of the exploration and exploitation of solid minerals in Nigeria with a special focus on tin in Jos and coal in Enugu. *Journal of Sustainable Mining*, 18(1):18–24. https://doi.org/10.1016/j.jsm.2018.12.001

Orellana, R., Cumsille, A., Piña-Gangas, P., Rojas, C., Arancibia, A., Donghi, S., Stuardo, C., Cabrera, P., Arancibia, G., Cárdenas, F., Salazar, F., González, M., Santis, P., Abarca-Hurtado, J., Mejías, M., and Seeger, M. 2022. Economic evaluation of bioremediation of hydrocarbon-contaminated urban soils in Chile. *Sustainability*, 14(19). https://doi.org/10.3390/su141911854

Osibote, I.A., Ogunjobi, A.A. and Okwuobi, N.P. 2014. Microbial Treatment of Complex Dyes Used in Local Textile Industries in Nigeria. *World Applied Sciences Journal*. 31(5):698-704. doi: 10.5829/idosi.wasj.2014.31.05.8390

Pan, J., Plant, J.A., Voulvoulis, N., Oates, C.J. and Ihlenfeld, C. 2010. Cadmium levels in Europe: implications for human health. *Environmental Geochemistry and Health*, 32(1):1–12. doi: 10.1007/s10653-009-9273-2

Perarlta-Videa, J.R.; Gardea-Torresdey, J.I.; Gomes, E.; Tiemann, K.J.; Parsons, J.G. and Carrillo, G. 2002. Effect of mixed cadmium, copper, nickel and zinc at different pH upon alfalfa growth and heavy metal uptake. *Environmental Pollution*, 119:291-302. https://doi.org/10.1016/s0269-7491(02)00105-7

Picardo, M.C., Ferreira, A.C. and Da Costa, A.C. 2009. Continuous thorium biosorption-dynamic study for critical bed depth determination in a fixed-bed reactor. *Bioresource Technology*, 100:208-210. https://doi.org/10.1016/j.biortech.2008.05.047

Pinto, A.P., Mota, A.M., de Varennes, A. and Pinto, F.C. 2004. Influence of organic matter on the uptake of cadmium, zinc, copper and iron by sorghum plants. *Science of the Total Environment*, 326:239-247. https://doi.org/10.1016/j.scitotenv.2004.01.004

Podolský, F., Ettler, V., Šebek, O., Ježek, J., Mihaljevič, M., Kříbek, B., Sracek, O., Vaněk, A., Penížek, V., Majer, V., Mapani, B., Kamona, F. and Nyambe, I. 2015. Mercury in soil profiles from metal mining and smelting areas in Namibia and Zambia: distribution and potential sources. *Journal of Soils and Sediments*, 15(3):648–658. https://doi.org/10.1007/s11368-014-1035-9

Putri, W.A.E., Meiyerani, J., Ulqodry, T.Z., Aryawati, R., Purwiyanto, A., Rozirwan, R. and Suteja, Y. 2025. Ecological risk assessment through heavy metal concentrations of lead, copper, cadmium, zinc, and nickel in marine sediments of Maspari Island, South Sumatra Indonesia. *Journal of Ecological Engineering*, 26(2):297–310. https://doi.org/10.12911/22998993/197413

Radwan M.A. and Salama A.K. 2006. Market basket survey for some heavy metals in Egyptian fruits and vegetables. *Food and Chemical Toxicology*, 44:1273-1278. http://dx.doi.org/10.1016/j.fct.2006.02.004

Rafeeq, H., Afsheen, N., Rafique, S., Arshad, A., Intisar, M., Hussain, A., Bilal, M., Iqbal, H.M.N. 2023. Genetically engineered microorganisms for environmental remediation. *Chemosphere*, *310*:136751. https://doi.org/https://doi.org/10.1016/j.chemosphere.2022.136751

Rai, V., Khatoon, S., Bisht, S.S. and Mehrotra, S. 2005. Effect of cadmium on growth, ultra morphology of leaf and secondary metabolites of *Phyllanthus amarus* Schum and Thonn. *Chemosphere*, 61:1644–1650. https://doi.org/10.1016/j.chemosphere.2005.04.052

Rensing, C., Ghosh, M. and Rosen, B. 1999. Families of soft-metal-ion-transporting ATPases. *Journal of Bacteriology*, 181:5891-5897. https://doi.org/10.1128/jb.181.19.5891-5897.1999

Rieuwerts, J.S., Ashnore, M.R., Farago, M.E. and Thornton, I. 2006. The influence of soil characteristics on the extractability of Cd, Pb and Zn in upland and moorland soils. *Science of the Total Environment*, 366:864-875. https://doi.org/10.1016/j.scitotenv.2005.08.023

Rizwan, M., Ali, S., Adrees, M., Ibrahim, M., Tsang, D.C.W., Zia-ur-Rehman, M., Zahir, Z.A., Rinklebe, J., Tack, F.M.G. and Ok, Y.S. 2017. A critical review on effects, tolerance mechanisms and management of cadmium in vegetables. *Chemosphere*, 182:90–105. https://doi.org/10.1016/j.chemosphere.2017.05.013

Roane, T.M. and Kellogg, S.T. 1996. Characterization of bacterial communities in heavy metal contaminated soils. *Canadian Journal of Microbiology*, 42:593-603. https://doi.org/10.1139/m96-080

Rodríguez-Eugenio, N., McLaughlin, M. and Pennock, D. 2018. Soil Pollution: A Hidden Reality. Rome: FAO.

Ryan, J.A., Zhang, P., Chou, J. and Sayers, D.E. 2001. Formation of chloropyromorphite in a lead-contaminated soil amended with hydroxyapatite. *Environmental Pollution*, 50:493–500. doi: 10.1016/j.envint.2003.07.001

Samanta, S.K., Singh, O.V. and Jain, R.K. 2002. Polycyclic aromatic hydrocarbons:

Environmental pollution and bioremediation. *Trends in Biotechnol*ogy, 20:243–248. https://doi.org/10.1016/S0167-7799(02)01943-1

Sanità di Toppi, L. and Gabbrielli, R. 1999. Response to cadmium in higher plants. *Environmental and Experimental Botany*, 41(2):105-130. https://doi.org/10.1016/S0098-8472(98)00058-6

Scebba, F., Arduini, I., Ercoli, L. and Sebastiani, L. 2006. Cadmium effects on growth and antioxidant enzymes activities in *Miscanthus sinensis*. *Biologia Plantarum*, 50:688-692. https://doi.org/10.1007/s10535-006-0107-0

Scott, J.A. and Karanjkar, A.M. 1992. Repeated cadmium biosorption by regenerated *Enterobacter aerogenes* biofilm attached to activated carbon. *Biotechnology Letters*, 14:737–740. https://doi.org/10.1007/BF01021653

Shah, A., Arjunan, A., Baroutaji, A., and Zakharova, J. 2023. A review of physicochemical and biological contaminants in drinking water and their impacts on human health. *Water Science and Engineering*, *16*(4):333–344. https://doi.org/10.1016/j.wse.2023.04.003

Sharma, D.C., Sharma, C.P. and Tripathi, R.D. 2003. Phytotoxic lesions of chromium in maize. *Chemosphere*, 51:63–68. https://doi.org/10.1016/S0045-6535(01)00325-3

Sharma, R.K., Agrawal, M. and Marshall, F. 2006. Heavy metals contamination in vegetables grown in wastewater irrigated areas of Varanasi, India. *Bulletin of Environmental Contamination and Toxicology*, 77:312-318. https://doi.org/10.1007/s00128-006-1065-0

Sharma, R.K., Agrawal, M. and Marshall, F.M. 2008a. Atmospheric deposition of heavy metals (Cu, Zn, Cd and Pb) in Varanasi City, India. *Environmental Monitoring and Assessment*, 142:269-278. https://doi.org/10.1007/S10661-007-9924-7

Sharma, R.K., Agrawal, M. and Marshall, F.M. 2008b. Heavy metal (Cu, Zn, Cd and Pb) contamination of vegetables in urban India: A case study in Varanasi. *Environmental Pollution*, 154:254-263. https://doi.org/10.1016/j.envpol.2007.10.010

Shukla, O.P., Dubey, S. and Rai, U.N. 2007. Preferential accumulation of cadmium and chromium: toxicity in *Bacopa monnieri* L. under mixed metal treatments. *Bulletin of Environmental Contamination and Toxicology*, 78:252–257. http://dx.doi.org/10.1007/s00128-007-9155-1

Singh, K.P., Mohon, D., Sinha, S. and Dalwani, R. 2004. Impact assessment of treated/untreated waste water toxicants discharge by sewage treatment plants on health, agricultural and environmental quality in waste water disposal area. *Chemosphere*, 55:227-255. doi: 10.1016/j.chemosphere.2003.10.050

Singh, S. and Kumar, M. 2006. Heavy metal load of soil, water and vegetables in peri-urban Delhi. *Environmental Monitoring and Assessment*, 120:79-91. https://doi.org/10.1007/s10661-005-9050-3

Sinha, S., Pandey, K., Gupta, A.K. and Bhatt, K. 2005. Accumulation of metals in vegetables and crops grown in the area irrigated with river water. *Bulletin of Environmental Contamination and Toxicology*, 74:210-218. https://doi.org/10.1007/s00128-004-0570-2

Sohi, M., Pitesky, M., and Gendreau, J. 2023. Analyzing public sentiment toward GMOs via social media between 2019-2021. *GM Crops and Food*, *14*(1):1–9. https://doi.org/10.1080/21645698.2023.2190294

Soleimani, N., Fazli, M.M. and Mehrasbi, M. 2015. Highly cadmium tolerant fungi: Their tolerance and removal potential. *Journal of Environmental Health Science and Engineering*, 13(19):1-9. http://dx.doi.org/10.1186/s40201-015-0176-0

Sone, Y., Mochizuki, Y., Koizawa, K., Nakamura, R., Pan-Hou, H., Itoh, T. and Kiyono, M.

2013. Mercurial-resistance determinants in Pseudomonas strain k-62 plasmid PMR68. A*MB Express*., 3:41. https://doi.org/10.1186/2191-0855-3-41

Song, P., Xu, D., Yue, J., Ma, Y., Dong, S., and Feng, J. 2022. Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review. *Science of the Total Environment*, 838(Part 3):156417. https://doi.org/10.1016/j.scitotenv.2022.156417

Souza Arroyo, V., Martínez Flores, K., Bucio Ortiz, L, Gómez-Quiroz, L.E. and Gutiérrez-Ruiz, M.C. 2012. Liver and cadmium toxicity. *Journal of Drug Metabolism* and *Toxicology*, 5(1). http://dx.doi.org/10.4172/2157-7609.S5-001

Stephens W.E and Calder A. 2005. Source and health implications of high toxic metal concentrations in illicit tobacco products. *Environmental Science and Technology*, 39:479–488.

Sthiannopkao, S. and Wong, M.H. 2013. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. *Science of The Total Environment*, 463–464:1147–1153. https://doi.org/10.1016/j.scitotenv.2012.06.088

Strzebońska, M., Jarosz-Krzemińska, E. and Adamiec, E. 2017. Assessing historical mining and smelting effects on heavy metal pollution of river systems over span of two decades. *Water, Air,* and *Soil Pollution*, 228(4). https://doi.org/10.1007/s11270-017-3327-3

Sukreeyapongse, O.; Panichsakspatana, S. and Hansen, H. 2002. Transfer of heavy metals from sludge amended soil to vegetables and leachates. Paper presented at the 17th World Congress of Soil Science (WCSS), 14th-21st August, 2002. Thailand. Symposium No. 29, Paper No. 1969.

Suruchi and Khanna, P. 2011. Assessment of heavy metal contamination in different vegetables grown in and around urban areas. *Research Journal of Environmental Toxicology*, 5:162-179. https://doi.org/10.3923/rjet.2011.162.179

Syed, A., Zeyad, M. T., Shahid, M., Elgorban, A. M., Alkhulaifi, M. M. and Ansari, I. A. 2021. Heavy metals induced modulations in growth, physiology, cellular viability, and biofilm formation of an identified bacterial isolate. *ACS Omega*, 6(38):25076–25088. http://dx.doi.org/10.1021/acsomega.1c04396

Talos, K., Pager, C. and Tonk, S. 2009. Cadmium biosorption on native *Saccharomyces cerevisiae* cells in aqueous suspension. *Acta Universitatis Sapientiae Agriculture and Environment*, 1:20-30.

Tandi, N.K., Nyumangara, J. and Bangara, C. 2005. Environmental and potential health effects of growing leafy vegetables on soil irrigated using sewage sludge and effluent: A case of Zn and Cu. *Journal of Environmental Science and Health*, 39:461-471. http://dx.doi.org/10.1081/PFC-120035930

Tindwa, H. and Singh, B. R. 2023. Soil pollution and agriculture in sub-Saharan Africa: State of the knowledge and remediation technologies. *Frontiers in Soil Science*, 2. https://doi.org/10.3389/fsoil.2022.1101944

Thompson, H.C. and Kelly, W.C. 1990. Vegetable Crops. 5th Edition. New Delhi: McGraw Hill Publishing Company Ltd.

Tőzsér, D., Magura, T. and Simon, E. 2017. Heavy metal uptake by plant parts of willow species: A meta-analysis. *Journal of Hazardous Materials*, 336:101–109. http://dx.doi.org/10.1016/j.jhazmat.2017.03.068

Tsalev, D.L. 1993. *Cadmium*. In: Atomic absorption spectrometry in occupational and environmental health practice. Tsalev DL (ed), Florida: CRC press. 1:105–112.

United State Environmental Protection Agency (USEPA) 2004. *Cleaning Up the Nation's Waste Sites: Markets and Technology Trends*. EPA 542-R-04-015.

United Nations Environment Programme 2024. Global Waste Management Outlook 2024: Beyond an Age of Waste – Turning Rrubbish into a Resource. Nairobi. https://wedocs.unep.org/20.500.11822/44939

Verma, N. and Singh, M. 2005. Biosensors for heavy metals. *Biometals*, 18:121–129. https://doi.org/10.1007/s10534-004-5787-3

Volpe, M.G., La Cara, F., Volpe, F., De Mattia, A., Serino, V., Petitto, F., Zavalloni, C., Limone, F., Pellecchia, R., De Prisco, P.P. and Di Stasio, M. 2009. Heavy metal uptake in the enological food chain. *Food Chemistry*, 117(3):553–560. https://doi.org/10.1016/j.foodchem.2009.04.033

Voutsa, D., Grimanis, A. and Samara, C. 1996. Trace elements in vegetables grown in an industrial area in relation to soil and air particulate matter. *Environmental Pollution*, 94(3):325-335. https://doi.org/10.1016/S0269-7491(96)00088-7

Walker, D.J., Clemente, R., Roig A. and Bernal, M.P. 2003. The effects of soil amendments on heavy metal bioavailability in two contaminated Mediterranean soils. *Environmental Pollution*, 122:303-312. http://dx.doi.org/10.1016/S0269-7491(02)00287-7

Wang, X., Sato, T., Xing, B. and Tao, S. 2005. Health risks of heavy metals to the general public in Tianjin, China via consumption of vegetables and fish. *Science of the Total Environment*, 350:28-37. https://doi.org/10.1016/j.scitotenv.2004.09.044

White, D.C., Flemming, C.A. Leung, K.T. and Macnaughton, S.J. 1998. In situ bacterial ecology for quantitative appraisal, monitoring and risk assessment of pollution remediation in soils, the subsurface, the rhizosphere and in biofilms. *Journal of Microbiological Methods*, 32:93-105. DOI: 10.1016/s0167-7012(98)00017-7

Wilcox, A.J., Savitz, D.A. and Samet, J.M. (2008). A tale of two toxicants: lessons from Minamata and Liaoning. *Epidemiology*, 19:1-2. https://doi.org/10.1097/ede.0b013e31815caa3

Witkowska, D., Słowik, J. and Chilicka, K. 2021. Heavy Metals and Human Health: Possible Exposure Pathways and the Competition for Protein Binding Sites. *Molecules*, 26:6060. https://doi.org/10.3390/molecules26196060

Wong, J.W.C. 1996. Heavy metal contents in vegetables and market garden soils in Hong Kong. *Environmental Technology*, 17:407-414. https://doi.org/10.1080/09593331708616400

Yang, Y., Zhang, L., Huang, X., Zhou, Y., Quan, Q., Li, Y., and Zhu, X. 2020. Response of photosynthesis to different concentrations of heavy metals in Davidia involucrata. *PLOS ONE*, *15*(3):e0228563. https://doi.org/10.1371/journal.pone.0228563

Yusuf, A.A., Arowolo, T.A and Bamgbose, O. 2003. Cadmium, copper and nickel levels in vegetables from industrial and residential areas in Lagos City, Nigeria. *Food and Toxicology*, 41:375-378. https://doi.org/10.1016/s0278-6915(02)00223-5

Yusuf, K.A. and Osibanjo, O. 2006. Trace metals in water and sediments from Ologe Lagoon, Southwestern Nigeria. *Pakistan Journal of Scientific and Industrial Research*, 49:88-96.

Zhu, Y.G., Chen, S.B. and Yang, J.C. 2004. Effects of soil amendments on lead uptake by two vegetable crops from a lead-contaminated soil from Anhui, China. *Environment International*, 30:351–356. https://doi.org/10.1016/j.envint.2003.07.001

Zulfiqar, U., Jiang, W., Xiukang, et al. 2022. cadmium phytotoxicity, tolerance, and advanced remediation approaches in agricultural soils; A comprehensive review. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.773815