

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

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## 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.

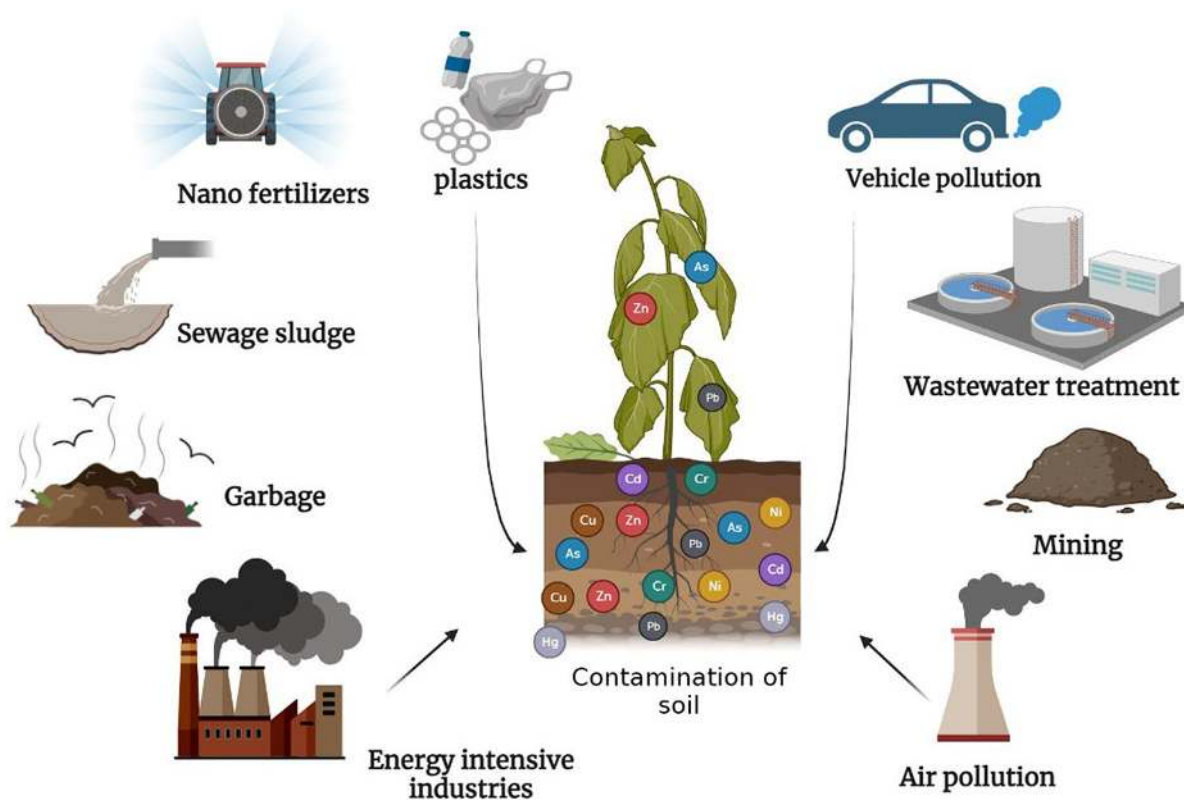
Heavy metals have been defined as elements that have more than 20 electrons with density higher than 5 g/cm<sup>3</sup> or 5 mg/mL (Jarup 2003; Witkowska et al. 2021). They possess characteristics such as electropositivity, density, ductility, conductivity, and ligand-specificity. Heavy metals include 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).

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).



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

Bioremediation, otherwise termed bioreclamation and biorestitution, 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*

(Kozłowski and Walkowrak 2002). *Pseudomonas* and *Alcaligenes* have been applied in the bioremediation of chromium (Kozłowski and Walkowrak 2002), and bacterial isolates such as *Pseudomonas* and *Escherichia* have been applied in bioremediating copper (Kozłowski 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).

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).

**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.*

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).

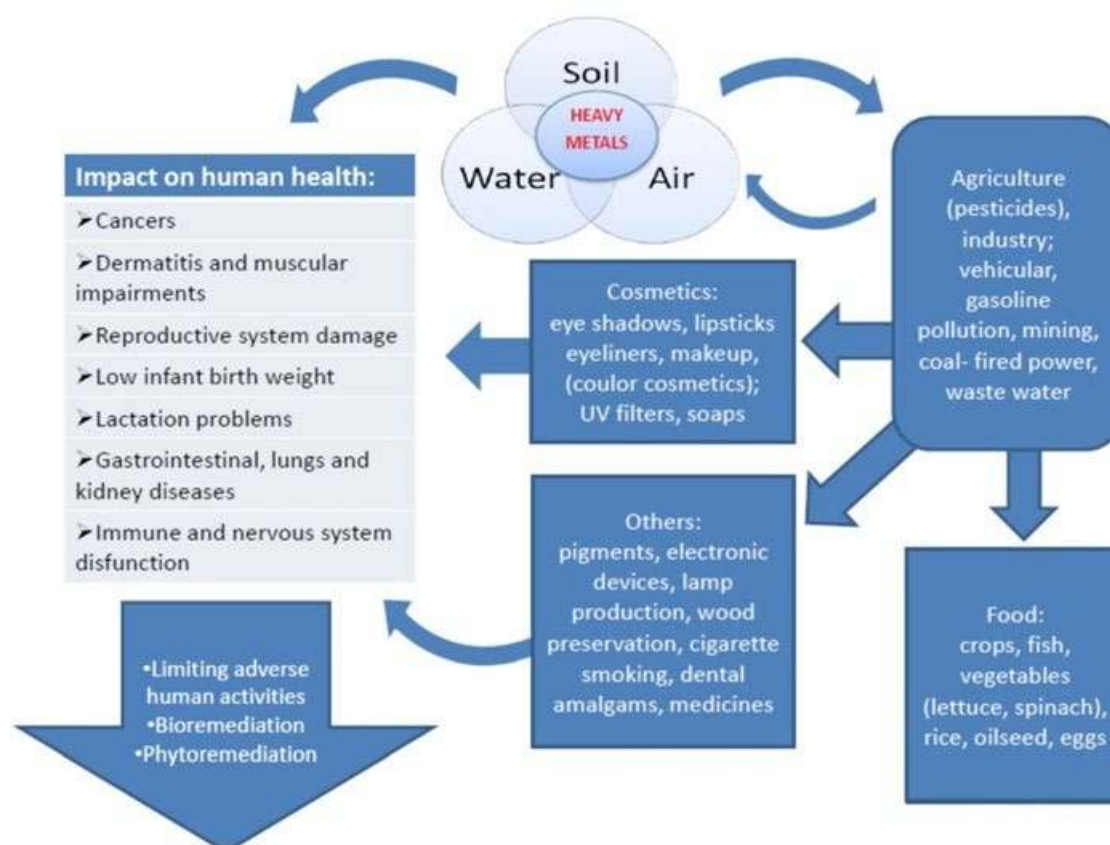
Consuming plants with high concentrations of these heavy metals can pose serious health risks to humans (Cui et al. 2004), depending on the heavy metal's physical characteristics, its chemical composition, the type of vegetable and the amount consumed (Anuoluwa et al. 2021). In recent years, the consumption 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 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).



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

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 or enzymatic 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 *Escherichia 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<sup>2+</sup> 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 (Azubuikwe 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.

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