Ogunsumi, Akintunde Israel, 2026, 14:4
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Mechanisms, Plant Species and Prospects of Phytoremediation in Managing Heavy Metal Contaminated Soils

Ogunsumi, Akintunde Israel[1], Awodiran Festus Tunde[2]
[1]Plant Ecology Unit, Department of Botany, University of Ibadan. Oyo state, Nigeria.
[2]Plant physiology and Biochemistry Unit, Department of Botany, University of Ibadan, Oyo state, Nigeria.

Abstract- Heavy metal pollution of soils in Nigeria, driven by activities such as mining, industrial discharge, waste disposal, and agricultural practices, poses a severe threat to environmental health, food safety, and human well-being. Conventional remediation methods are often costly, invasive, and environmentally disruptive. Phytoremediation, a green and cost-effective technology using plants to extract, stabilize, or degrade contaminants has emerged as a promising alternative for addressing soil contamination in Nigeria. This review explores the mechanisms of phytoremediation, including phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration, with a focus on their application to heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg). Several plant species indigenous or adaptable to Nigerian soils, including Chromolaena odorata, Chromolaena odorata, Brassica juncea, Helianthus annuus, and Tithonia diversifolia have demonstrated phytoremediation potential. Despite promising research, major knowledge gaps remain in understanding plant-metal interactions under local soil and climatic conditions, the long-term sustainability of remediation outcomes, and strategies for integrating phytoremediation into national environmental policies. Challenges such as low biomass yield, metal toxicity to plants, and limited public awareness hinder large-scale implementation. Future research should focus on genetic improvement of hyperaccumulators, synergistic use of soil amendments and microbes, and development of region-specific phytoremediation models. Strengthening collaboration among researchers, government agencies, and local communities is crucial to fully harness the potential of phytoremediation for sustainable soil management and environmental restoration in Nigeria.

Keywords— Environmental restoration, Heavy metal pollution, Hyperaccumulator, Soil contamination, Phytoremediation,

I. INTRODUCTION

1. Background on Heavy Metal Pollution in Nigeria

Heavy metal pollution has become a significant environmental concern in Nigeria, primarily due to rapid industrialization, urbanization, and unsustainable agricultural and mining practices, (Laoye et al., 2025). Heavy metals, such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr), are non-biodegradable and persist in the environment, leading to bioaccumulation, bio-magnification, long-term ecological and human health risks (Ali et al., 2019). In Nigeria, the presence of these metals in soils, water bodies, and air has been widely reported, particularly in industrial, mining, and oil-producing regions.

Table 1 presents a summary of selected studies conducted across various regions of Nigeria, highlighting the presence and impact of heavy metal contamination due to mining and industrial activities. The table outlines the study locations, specific heavy metals identified, and key findings related to environmental and health risks associated with the contamination.

Table 1: Studies on Heavy Metal Contamination from Mining and Industrial Activities in Nigeria

Author(s) and year	Study location	Heavy metals identified	Findings
Okonkwo *et al.* (2021)	Olode, SW Nigeria	Ni, Cr	High contamination due to Ni and Cr from pegmatite mining.
Yahaya *et al.* (2021)	Zamfara State	Pb, Cd	Artisanal mining accounts for 98.64% of the total ecological risk.
Adekiya *et al.* (2024)	Ilesha, Nigeria	Various	Heavy metal pollution is significant but below intervention thresholds.
Adewumi and Laniyan (2023)	Arufu, NE Nigeria	Pb, Zn, F	Mining activities contaminate water, posing ecological and health risks.
Oluwasola *et al.* (2021)	Oke-Ere, Kogi State	Sc, Sn	High Sc pollution, moderate Sn levels, and high cancer risk via ingestion and dermal exposure.
Kolawole *et al.* (2018)	SW Nigeria (Industrial area)	Cd, Pb, Cu	Very high contamination with ecological risks.
Ugochukwu *et al.* (2022)	Ebonyi State	Various	Galena mining has polluted soil, sediment, and water, with economic costs from $20.7M to $543.33M.
Olatunde *et al.* (2020)	Ibese, Ogun State	Cd, Cr, Ni, Pb	Cement factory activities contribute to pollution and ecological risk.
Badamasi *et al.* (2022)	Riruwai, NW Nigeria	Various	High contamination, particularly in active and abandoned sites.
Akinnifesi *et al.* (2021)	SW Nigeria	Various	Heavy metals affect soil, water, and air, impacting ecosystem functions.

Sources of Heavy Metal Pollution

The major sources of heavy metal contamination in Nigeria include:

Mining Activities: Nigeria is rich in mineral resources, with extensive mining operations in states like Zamfara, Osun, Niger, Kano, Ebonyi, Enugu, Plateau, etc.

Gold mining, particularly illegal and artisanal activities, has significantly impacted the environment and public health in Osun State, Nigeria. The contamination of water bodies, soil pollution, and human exposure to toxic metals are critical concerns. Illegal gold mining in Ilesa-West Local Government Area has resulted in severe contamination of stream water and sediments with toxic metals, posing serious health risks to local communities (Makinde et al., 2013). Similarly, gold mining activities in the Osun River have significantly degraded its water quality, endangering freshwater biodiversity and human health (Akindele et al., 2023). Additionally, in Ijeshaland, trace metal concentrations in surface water and fish are elevated, increasing health risks for individuals consuming aquatic organisms from the region (Taiwo and Awomeso, 2017).

Beyond water contamination, heavy metal pollution is prevalent in soils and mine tailings at key gold mining sites such as Igun, Ijana-Gada, and Igbadae. These areas are contaminated with vanadium (V), titanium (Ti), and chromium (Cr) from anthropogenic sources, posing severe environmental and health hazards (Awoyelu and Mebo, 2023).

Toxic metal exposure from gold mining has considerable health implications. Arsenic contamination from illegal mining in Igun presents heightened health risks for both adults and children, particularly through dermal exposure (Olujimi et al., 2015). Additionally, children in gold mining communities have been found to have significantly higher blood lead levels compared to those in non-mining areas, highlighting the urgent need for safer mining practices and routine lead toxicity screening (Akinwumi et al., 2023).

In Kano state, artisanal gold mining is widespread in Shanono and Bagwai local government areas, posing a serious risk to drinking water quality. Elevated levels of radon, as well as excessive gross alpha and beta radioactivity, surpass recommended safety thresholds, raising public health concerns (Bello et al., 2020).

In Ebonyi State, mining communities experience severe environmental challenges, further worsened by insufficient media attention and a lack of environmental awareness initiatives. These factors have contributed to declining agricultural productivity and increasing health issues in the region (Obasi and Msughter, 2023).

Benue State has also been significantly affected by unregulated mining activities, particularly due to high concentrations of lead detected in both water sources and human blood samples. This underscores the urgent need for improved regulatory measures to mitigate environmental and health risks associated with mining contaminants (Paul et al., 2023).

Barite mining in Nasarawa State is primarily carried out by artisanal and small-scale miners. However, the sector struggles with inefficiencies, inadequate government intervention, and weak enforcement of mining regulations, all of which hinder sustainable mining practices (Otoijamun et al., 2021).

Similarly, large-scale extraction of tin in Plateau State and coal mining in Enugu State have left lasting environmental damage, including extensive landscape degradation and pollution. Implementing stringent environmental policies and effective land reclamation strategies is essential to restoring affected areas (Omotehinse and Ako, 2019).

Zamfara State has become a hub for illegal gold mining, which has fueled insecurity and conflict in the region. The involvement of local traditional authorities in supporting illicit mining operations has further complicated socio-political stability (Itodo, 2023).

In Niger State, abundant mineral resources such as gold, coal, and barite are predominantly mined through informal and small-scale operations. The absence of proper management has led to widespread environmental degradation and inefficient resource utilization (Mustafa et al., 2020). Meanwhile, excessive sand mining in Sokoto State has caused severe vegetation loss and landscape deterioration. Limited restoration efforts emphasize the need for more effective ecological rehabilitation strategies to enhance environmental resilience (Agbaje et al., 2020).

Fig. 1 illustrates the geographical distribution of mining activities across various locations in Nigeria. Many of these sites have become hotspots for illegal and unregulated mining, especially in rural and resource-rich regions. Unfortunately, the operations of illegal miners often leave devastating impacts on the environment. Without adherence to environmental regulations or rehabilitation measures, these activities strip the land of its natural vegetation, leading to forest degradation and loss of biodiversity.

After extracting valuable minerals, illegal miners frequently abandon the sites, leaving behind scarred landscapes and polluted ecosystems. The soil and water bodies in these areas become heavily contaminated with toxic heavy metals such as lead, cadmium, chromium, and nickel, which persist in the environment and pose serious health and ecological risks. This ongoing environmental abuse not only compromises the integrity of Nigeria's ecosystems but also threatens the livelihoods and well-being of surrounding communities.

Fig. 1. Mining activities in Nigeria (Source: HumAngle, September 1, 2021. Retrieved from [https://humanglemedia.com/How Illegal Mining Is Contributing To Local Conflicts In Nigeria/]

2). Industrial discharges have been consistently identified as a critical source of heavy metal pollution in Nigeria, contributing significantly to the degradation of soils, surface and groundwater resources, and the contamination of food chains (Kolawole et al., 2018, Oloruntoba et al., 2024). The accelerated pace of industrialization across various regions of the country, coupled with weak environmental regulations and the widespread neglect of sustainable waste management practices, has exacerbated this environmental challenge. Numerous studies have documented the presence of elevated concentrations of toxic metals in areas surrounding industrial facilities, raising serious concerns about ecological integrity and public health safety (Egbueri et al., 2022).

Key industrial activities such as cement production, textile processing, battery recycling, and paint manufacturing are especially culpable, as they often discharge untreated or poorly treated effluents directly into nearby water bodies and onto land surfaces. These discharges contain hazardous heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni), iron (Fe), and manganese (Mn), which accumulate in the environment and persist over long periods due to their non-biodegradable nature (Olatunde et al., 2020).

Industrial zones such as Challawa in Kano State, Ota in Ogun State, Shagamu, and Ibese are notably affected. In these regions, environmental monitoring has shown that the levels of heavy metals in effluents, soils, and nearby water bodies frequently exceed both national and international safety thresholds. The persistence of these contaminants poses long-term risks to human health, especially for communities that rely on local water sources for drinking, irrigation, and fishing, as well as for agricultural activities where crops may absorb these metals from contaminated soils (Zacheus et al., 2020; Adeyemi et al., 2021; Darma et al., 2024).

Scientific investigations and environmental assessments have underscored the urgency of addressing this issue through stricter enforcement of environmental regulations, investment in effluent treatment technologies, and the adoption of cleaner production methods. Studies by Kolawole et al. (2018), Zacheus et al. (2020), Olatunde et al. (2020), Adeyemi et al. (2021), Egbueri et al. (2022), and more recently, Darma et al. (2024), have all provided empirical evidence of the elevated concentrations of heavy metals in and around industrial facilities, highlighting the pressing need for remedial and preventive strategies to mitigate their impacts on ecosystems and human populations.

To further contextualize the geographical distribution and severity of heavy metal contamination resulting from industrial discharges in Nigeria, Table 2 presents selected industrial zones where key heavy metals have been consistently detected. These locations; Challawa in Kano State, Ota and Shagamu in Ogun State, and Ibese in Ogun State, have been the focus of multiple environmental assessments due to their dense industrial activities. The table highlights the specific heavy metals identified in each location, such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni), and iron (Fe), as well as notable findings from recent studies. For instance, effluent and soil samples from Challawa were found to contain metal concentrations significantly above permissible safety thresholds. Similarly, groundwater sources in Ota and Shagamu have been reported as unsafe for human consumption due to elevated levels of heavy metals. In Ibese, emissions from cement manufacturing processes have contributed substantially to soil contamination. These findings underscore the environmental and public health implications of unchecked industrial waste disposal practices in Nigeria.

Table 2: Key Heavy Metals Detected and Notable Findings in Selected Industrial Areas of Nigeria

s/n	Location	Key Metals Detected	Notable Findings
1.	Challawa, Kano	Pb, Cd, Cr, Cu, Zn	Effluent and soil levels far above safe limits (Darma *et al.* 2024)
2.	Ota and Shagamu	Pb, Cd, Ni, Cr, Fe	Groundwater unsafe for consumption (Olatunde *et al.* 2020; Adeyemi *et al.* 2021)
3.	Ibese (Cement)	Cd, Cr, Ni, Pb	Soil pollution from cement factory emissions (Egbueri *et al.* 2022)

3). Agricultural Practices: Heavy metal contamination arising from agricultural practices in Nigeria represents a significant and growing environmental and public health challenge. Agricultural activities contribute substantially to the accumulation of toxic metals in soils and food crops, thereby increasing the risk of dietary exposure among consumers. Key sources of contamination include the widespread use of chemical fertilizers and pesticides, irrigation with polluted water, and the cultivation of crops on already contaminated lands, such as former industrial sites, mining zones, or reclaimed refuse dumps.

Chemical fertilizers and pesticides, often used indiscriminately in intensive farming systems, are known to contain trace amounts of heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), and zinc (Zn). These metals accumulate in agricultural soils over time and are absorbed by crops, especially under conditions of repeated application. Studies have shown that concentrations of these metals in soils and edible plant parts can frequently exceed internationally recognized safety thresholds, particularly in areas where pesticide-treated water is used for irrigation or where land is subjected to over-cultivation (Onakpa et al., 2018; Bawa, 2023; Folarin et al., 2023). Additionally, the use of contaminated irrigation water, whether from sources affected by agricultural runoff, livestock waste, industrial effluents, or municipal sewage, further facilitates the introduction of heavy metals into the agricultural ecosystem. This contamination pathway is particularly concerning in peri-urban and rural communities where untreated wastewater is often reused for farming due to water scarcity (Onakpa et al., 2018; Bawa, 2023). Over time, these practices not only degrade soil health but also compromise crop safety and food quality.

Furthermore, farming activities conducted near industrial zones or on reclaimed waste dumpsites are especially prone to heavy metal uptake by crops. Even when metal concentrations in edible portions of crops remain below regulatory limits, chronic exposure to low doses over time can pose serious health risks to consumers, including neurological, renal, and developmental disorders (Sagbara et al., 2020; Sani et al., 2023). These findings highlight the need for stricter monitoring, safer agricultural practices, and comprehensive risk assessments to safeguard food security and public health in Nigeria. Table 3 presents the primary agricultural sources of heavy metal contamination in Nigeria, the key metals associated with each source, and their corresponding health and environmental impacts. It highlights how the use of chemical fertilizers and pesticides, irrigation with contaminated water, and the cultivation of crops on waste sites contribute to the accumulation of toxic metals such as cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) in agricultural soils and produce. The table also references relevant studies that document the risks posed by these practices, including soil and water pollution, crop contamination, and long-term health implications for exposed populations.

Table 3: Agricultural Sources of Heavy Metal Contamination, Key Metals, and Associated Impacts in Nigeria

s/n	Agricultural Source	Main Heavy Metals Introduced	Health/Environmental Impact	Citations
1.	Fertilizers/Pesticides	Cd, Pb, Cr, Cu, Zn	Crop contamination, human health risks	(Onakpa *et al.,* 2018; Bawa, 2023; Folarin *et al.,* 2023)
2.	Contaminated Irrigation	Cd, Fe, Mn, Pb	Soil/water pollution, crop uptake	(Onakpa *et al.,* 2018; Bawa, 2023).
3.	Cultivation on Waste Sites	Zn, Cu, Pb	Chronic exposure, potential health effects	(Sagbara *et al.,* 2020; Oloruntoba *et al.,* 2020; Sani *et al.,* 2023).

4). Petroleum Exploration and Oil Spills: The Niger Delta region of Nigeria is heavily burdened by environmental contamination from heavy metals, primarily due to extensive oil exploration, frequent oil spills, gas flaring, and various industrial operations. These anthropogenic activities have introduced elevated concentrations of toxic metals including lead (Pb), nickel (Ni), cadmium (Cd), and chromium (Cr) into the environment. These contaminants have been consistently detected in the region's soil, surface water, groundwater, aquatic sediments, and seafood, posing significant ecological and public health concerns (Onyena et al., 2024; Chinedu and Chukwuemeka, 2018; Izah et al., 2017).

The primary sources of this heavy metal pollution include crude oil spills, flaring of associated gas, and discharges from industrial facilities. Additionally, local agricultural practices and cassava processing activities contribute to the accumulation of these toxic elements in the environment (Onyena et al., 2024; Chinedu and Chukwuemeka, 2018; Izah et al., 2017). Among the affected areas, Rivers State frequently reports the highest levels of contamination, indicating a persistent pattern of environmental degradation in key oil-producing zones (Nduka and Orisakwe, 2011; Umeoguaju et al., 2022).

Although remediation efforts have been carried out in certain locations, significantly reducing contamination levels in those sites, ongoing environmental monitoring remains essential due to the continued presence of pollution sources and the long-term persistence of heavy metals in ecosystems.

Alarmingly, many analyzed samples from soil, water, and seafood exceed the maximum allowable concentrations set by the World Health Organization (WHO) and the United States Environmental Protection Agency (US EPA), underscoring the need for stronger regulatory enforcement and sustainable remediation strategies (Umeoguaju et al., 2023; Nduka and Orisakwe, 2011; Olawoyin et al., 2012; Eyankware et al., 2023).

Table 4 presents a some of key heavy metals detected in various environmental media including soil, groundwater, surface water, and seafood, within the context of environmental pollution studies in Nigeria. The table highlights the specific metals identified, their measured concentrations (in mg/kg or mg/L), and whether these values exceed internationally recognized safety limits such as those set by the WHO or other regulatory bodies.

Table 4: Detected Levels of Heavy Metals in Soil, Water, and Seafood Compared to Safety Standards in Nigeria

s/n	Medium	Key Metals Detected (mg/kg or mg/L)	Above Safe Limits?	Citations
1.	Soil	Pb (895), Ni (43), Cd (1.3), Cr (13), Zn (58), Fe (1303)	Yes	(Nduka and Orisakwe, 2011; Olawoyin *et al.,* 2012)
2.	Groundwater	Pb, As, Cd (all above WHO limits)	Yes	Eyankware *et al.,* 2023; Ejike *et al.,* 2017)
3.	Surface Water	Fe, Mn, Cu, Cd, Cr, Pb, Ni, Zn	Yes	Umeoguaju *et al.,*2022
4.	Seafood	Fe (143), Zn (29), Ni (5), Pb (4), Cd (1)	Yes	Umeoguaju *et al.,*2023

Improper Waste Disposal: Improper waste management, particularly the mishandling of municipal, construction, and electronic waste, remains a critical source of heavy metal contamination in urban environments. Practices such as open dumping, unmanaged landfilling, incineration, and informal e-waste recycling contribute significantly to the release of hazardous heavy metals into soil, water, and air. Notably, these activities introduce toxic elements including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and arsenic (As) into the environment through several pathways:

Landfills and Dumpsites: Both sanitary and unsanitary landfills produce leachate rich in heavy metals, which can migrate into surrounding soils and aquatic ecosystems. Non-sanitary landfills, in particular, are associated with elevated concentrations of arsenic, cadmium, and other metals. Pollution indices in these areas often indicate moderate to strong contamination, underscoring the need for better waste containment and treatment infrastructure (de Souza et al., 2023; Nyiramigisha, 2021).

Incineration of Municipal Solid Waste: Incineration generates fly ash containing concentrated levels of heavy metals such as Pb, Cd, Cr, Zn, and Hg. When this ash is disposed of improperly, especially in regions lacking strict regulatory oversight, it can lead to widespread environmental contamination and long-term ecological risks (Wang et al., 2019).

Construction Waste Disposal: Prolonged accumulation and disposal of construction debris have been shown to increase heavy metal concentrations, especially cadmium, zinc, lead, and copper in nearby soils. The highest levels of pollution are typically observed within the boundaries of landfill sites where construction waste is deposited (Wu et al., 2022).

Informal E-waste Recycling: Unregulated recycling of electronic waste is one of the most toxic contributors to urban heavy metal pollution. Informal processing methods release substantial amounts of Pb, Cd, Cr, Cu, and Hg into the surrounding environment, contaminating soil, water, air, and even nearby agricultural products. Studies have shown that these concentrations frequently exceed international safety thresholds, posing significant health hazards to nearby populations (Houessionon et al., 2021; Song and Li, 2014; He et al., 2017). Table 5 describes major waste sources and the heavy metals they release, along with associated environmental impacts as documented in recent studies.

Table 5: Major Waste Sources, Associated Heavy Metals, and Their Environmental Impacts

s/n	Source of Waste	Main Heavy Metals Released	Environmental Impact	Citations
1.	Landfills/Dumpsites	As, Cd, Pb, Zn, Cu, Cr, Mn	Soil/water contamination, crop uptake	(Hussein *et al.* 2021; de Souza *et al.* 2023; Nyiramigisha, 2021)
2.	Incineration Fly Ash	Pb, Cd, Cr, Zn, Hg, Cu, Ni, As	Air/soil pollution, ecological risk	Wang *et al.* 2019
3.	E-waste Recycling	Pb, Cd, Cr, Cu, Hg, As	Soil, water, air, food contamination	(Houessionon *et al.* 2021; He *et al.* 2017)
4.	Construction Waste	Cd, Zn, Pb, Cu, Cr	Soil pollution, ecological risk	Wu *et al.* 2022

Environmental and health risks

Heavy metal pollution in Nigeria poses significant environmental and health risks, largely stemming from mining, industrial discharges, agriculture, and petroleum exploration. Each of these sources introduces toxic metals such as lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and nickel (Ni) into ecosystems, where they persist due to their non-biodegradable nature. From a public health perspective, chronic exposure to these metals, even in small quantities, can result in neurological disorders, kidney damage, developmental abnormalities in children, cancers, and cardiovascular diseases. Environmentally, they compromise soil fertility, reduce agricultural productivity, degrade water quality, and threaten biodiversity in aquatic and terrestrial habitats (Adeyemi and Ojekunle, 2021; Bawa-Allah, 2023; Chris et al., 2023; Oyebamiji et al., 2024). Heavy metal contamination has profound environmental and human health effects in Nigeria:

Soil Degradation: The. Heavy metal contamination from mining, industrial, and roadside activities in Nigeria leads to soil pollution exceeding safe limits, which degrades soil quality, threatens agricultural productivity, and poses risks to human and environmental health. (Ezeh and Chukwu, 2011). This poses a threat to food security and agricultural sustainability. The accumulation of toxic metals in soil alters its physicochemical properties, reducing fertility and microbial diversity

Water Contamination: Rivers and groundwater sources contaminated by heavy metals pose risks to human health and aquatic life. Heavy metal contamination of water sources in Nigeria is a significant environmental and public health concern, with studies consistently reporting levels of metals such as lead, cadmium, chromium, arsenic, and mercury exceeding World Health Organization (WHO) and national safety standards in both surface and groundwater across various regions. Industrial activities, especially mining and tannery operations, are major contributors, as seen in areas like Kano and Abakaliki, where water near industrial sites contains dangerously high concentrations of chromium, lead, and other toxic metals. These contaminants pose serious health risks, including neurological disorders, cancer, kidney damage, and developmental issues, particularly affecting children and vulnerable populations. Ecological impacts are also severe, threatening aquatic life and reducing the suitability of water for domestic and agricultural use (Izah et al., 2016; Obasi and Akudinobi, 2020.Bawa-Allah, 2023)

Human Health Risks: Heavy metal contamination poses significant risks to both the environment and human health, primarily due to the persistence and bioaccumulation of metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) in soil, water, and food chains. Chronic exposure to these metals can result in a range of health problems, including neurological disorders, kidney damage, cardiovascular diseases, reproductive toxicity, and various cancers, with children being particularly vulnerable to cognitive impairment and developmental delays from lead exposure (Laoye et al., 2025; Adimalla et al., 2020; Rahman et al., 2019; Zheng et al., 2020). Studies across urban, industrial, and agricultural regions worldwide have consistently found heavy metal concentrations exceeding safe background levels, with ingestion of contaminated food (especially rice, vegetables, and grains), direct soil contact, and water consumption identified as major exposure pathways (Aziz et al., 2023; Zheng et al., 2020). Health risk assessments reveal that non-carcinogenic risks (such as those from Pb and Cr) and carcinogenic risks (notably from Cd, Cr, and Ni) often surpass acceptable safety thresholds, especially for children, who face higher hazard indices and cancer risks than adults (Zerizghi et al., 2022; Upadhyay et al., 2024). Industrial activities, mining, traffic emissions, and the use of fertilizers and pesticides are key contributors to environmental heavy metal burdens (Laoye et al., 2025; Aziz et al., 2023). In many affected regions, dietary intake of contaminated crops is the predominant route of human exposure, underscoring the importance of food safety monitoring (Zheng et al., 2020). Effective mitigation strategies include policy interventions, community engagement, technological innovations, and sustainable remediation methods such as phytoremediation and chelation therapy . The global and persistent nature of heavy metal pollution highlights the urgent need for integrated management approaches to protect both ecosystems and public health (Laoye et al., 2025; Adimalla et al., 2020).

Biodiversity Loss: Heavy metal contamination poses a significant threat to both environmental biodiversity and human health due to its persistence, toxicity, and ability to bioaccumulate in ecosystems. In contaminated environments, heavy metals such as mercury, cadmium, lead, and arsenic disrupt plant growth, reduce soil microbial diversity, and cause declines in wildlife populations, leading to biodiversity loss and ecosystem dysfunction. Aquatic systems are particularly vulnerable, as heavy metals accumulate in fish and other organisms, entering the food web and posing direct risks to human consumers, as seen with mercury bioaccumulation in fish species in regions like the Niger Delta. Human exposure to these metals, primarily through contaminated food and water, is linked to a range of health issues including neurological disorders, kidney damage, and increased cancer risk, with children being especially susceptible. The risk is exacerbated in developing regions where industrial activities, mining, and inadequate regulation contribute to higher contamination levels and greater socio-economic impacts4. Effective management requires integrated risk assessment, targeted monitoring, and sustainable mitigation strategies such as phytoremediation and stricter pollution controls (Zerizghi et al., 2022; Bishnu Agnon et al., 2024; Laoye et al., 2025).

2. Why Phytoremediation?

Comparison with other remediation techniques (e.g., physical, chemical methods)

Phytoremediation, which uses plants to remove, stabilize, or degrade environmental contaminants, is increasingly favoured over traditional physical and chemical remediation methods due to its cost-effectiveness, sustainability, and minimal environmental disruption. Unlike conventional techniques, which are often expensive, invasive, and can generate secondary pollution, phytoremediation is a green, solar-powered approach that harnesses natural plant processes to clean up soils, water, and even air, making it especially suitable for large-scale or low-to-moderate contamination scenarios (Ashraf et al., 2019; Sarwar et al., 2017; Shah and Daverey , 2020; Kafle et al., 2022).

While physical and chemical methods can be faster and more thorough for highly contaminated sites, they often require significant energy input, specialized equipment, and can harm soil structure and biodiversity (Liu et al., 2020; Sabreena et al., 2022). In contrast, phytoremediation is less disruptive, can improve soil health, and is adaptable to various contaminants, including heavy metals, organic pollutants, and radionuclides (Shah and Daverey , 2020; Meagher, 2000, Wei, et al., 2021). However, phytoremediation is generally slower and may be less effective for sites with very high contaminant concentrations or where rapid cleanup is required (Liu et al., 2020). Recent advances, such as combining phytoremediation with microbial or chemical amendments and genetic engineering, are helping to overcome these limitations and expand its applicability (Mocek-Płóciniak et al., 2023; Kafle et al., 2022). Phytoremediation, therefore stands out as an environmentally friendly, economically viable, and sustainable alternative, particularly for long-term management and restoration of contaminated environments (Gerhardt et al., 2017).

Benefits and limitations of using plants for remediation

Fig 2 presents a comprehensive overview of the advantages and limitations associated with phytoremediation processes for the removal of heavy metals from tropical soils. As an eco-friendly and cost-effective strategy, phytoremediation leverages the natural abilities of certain plants to extract, stabilize, or degrade contaminants in the soil. The figure highlights key benefits of this technique, including minimal disturbance to the soil ecosystem, enhancement of soil fertility through organic matter addition, and the potential for biomass recovery and utilization. However, it also illustrates notable challenges such as slow remediation rates, the risk of metal re-mobilization, plant species selectivity, and limitations under extreme contamination or adverse climatic conditions.

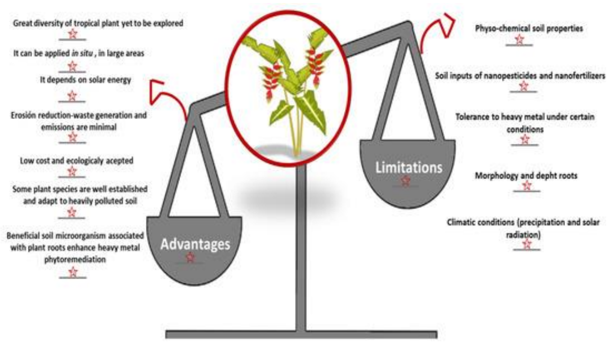

Fig 2. Advantages and limitations in phytoremediation processes to remove heavy metals from tropical soils (Adapted from Guerra Sierra et al., 2021).

II. MECHANISMS OF PHYTOREMEDIATION

Phytoremediation offers a sustainable alternative by harnessing the natural capabilities of plants to accumulate, stabilize, or transform contaminants into less harmful forms. This green technology has attracted considerable attention due to its low cost, public acceptance, and potential for land rehabilitation. The success of phytoremediation depends on several mechanisms, each tailored to specific contaminants and site conditions. The four major mechanisms of phytoremediation include: phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization (de Souza et al., 2023). Fig. 3 illustrates the major mechanisms involved in the phytoremediation of heavy metal-contaminated environments.

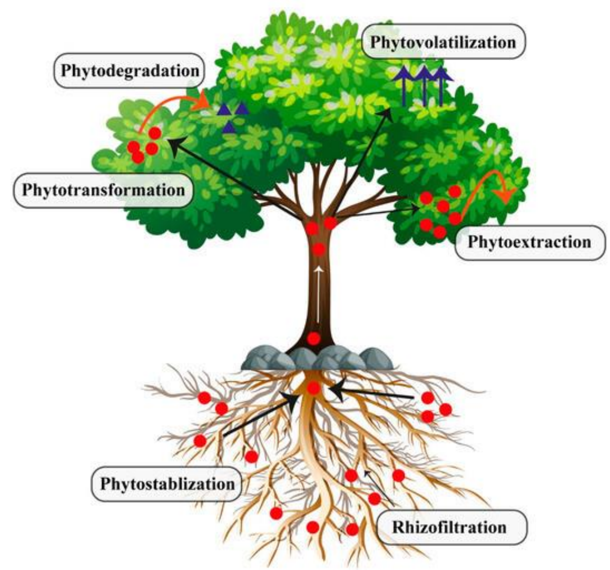

Fig 3: Mechanisms of Phytoremediation (Adapted from Wijekoon etal., 2025)

1. Phytoextraction

Hyperaccumulator plant species are crucial for phytoextraction, a process that uses plants to remove toxic metals from contaminated soils. Notable hyperaccumulators include Sedum plumbizincicola and Sedum alfredii for cadmium and zinc, Pteris vittata for arsenic, Alyssum species for nickel, Neptunia amplexicaulis for selenium, and Leersia hexandra for chromium, among others (Li et al., 2018; Zhou et al., 2020; Hou et al., 2017; O'Donohue et al., 2022; Zhang et al., 2023; Chaney et al., 2007). These plants can accumulate exceptionally high concentrations of specific metals in their tissues without suffering toxicity, making them effective for remediating polluted environments. For example, Sedum plumbizincicola and S. alfredii have demonstrated strong cadmium and zinc uptake, while Pteris vittata is widely used for arsenic removal (Zhou et al., 2020; Hou et al., 2017;

Li et al., 2018, Zeng et al., 2019). The efficiency of phytoextraction depends on both the plant species and soil conditions, such as pH and metal availability, with some species performing better in acidic or alkaline soils (Huang et al., 2020). Advances in understanding plant-microbe interactions and rhizosphere characteristics have further improved metal uptake and tolerance in these hyperaccumulators (Hou et al., 2017; Li et al., 2021; Zhang et al., 2023). While Brassica juncea (Indian mustard) is often mentioned, it is not a true hyperaccumulator and is less effective compared to specialized species like Thlaspi caerulescens for cadmium or Alyssum for nickel (van Der Ent and Rylott, 2024; Chaney et al., 2007). Ongoing research continues to identify new hyperaccumulators and optimize their use for large-scale environmental cleanup and even metal recovery (phytomining) (van Der Ent and Rylott, 2024; Li et al., 2021; Chaneyet al., 2007).

2. Phytostabilization

Phytostabilization is a sustainable remediation strategy that uses plants to immobilize heavy metals in contaminated soils, reducing their mobility and environmental risk without removing the contaminants themselves. The primary goal of phytostabilization is not to remove contaminants but to prevent their spread to surrounding environments or groundwater. The effectiveness of phytostabilization depends on selecting appropriate plant species, often those with extensive root systems and high metal tolerance, such as perennial ryegrass, Koelreuteria paniculata, and certain native grasses such as Vetiveria zizanioides (vetiver grass) and Populus spp , which can accumulate metals in their roots while limiting translocation to shoots, thus minimizing entry into the food chain (Nagy et al., 2024; Cheraghi et al., 2011; Wang et al., 2024). Soil amendments like composted sewage sludge, spent mushroom compost, and attapulgite can further enhance phytostabilization by improving soil pH, fertility, and structure, as well as reducing the bioavailability and leaching of heavy metals such as Mn, Pb, Zn, Cd, Cu, and Ni (Nagy et al., 2024; Hazratqulov et al., 2024). These amendments also support plant growth and beneficial soil microbial communities, which play a crucial role in stabilizing metals and restoring soil health (Wang et al., 2024; Lin et al., 2021).

The choice and processing of organic amendments are critical, as their effectiveness varies depending on the type of waste, treatment method, and specific contaminants present (Hazratqulov et al., 2024; Nagy et al., 2024) . While phytostabilization does not remove heavy metals, it offers long-term containment, reduces erosion and dust, and supports ecological restoration, making it particularly suitable for mine tailings, waste dumps, and highly contaminated sites where conventional remediation is impractical or too costly (Ashraf et al., 2019; Mahar et al., 2016; Bakshe and Jugade, 2023). Phytostabilization is recognized as a cost-effective, non-invasive, and environmentally friendly approach for managing heavy metal-contaminated soils (Sarwar, 2017).

3. Rhizofiltration

Rhizofiltration is a phytoremediation technique that uses the roots of aquatic or hydroponically grown terrestrial plants to remove heavy metals from contaminated water, offering a cost-effective and environmentally friendly alternative to conventional treatment methods. Plants such as Indian mustard, sunflower, water hyacinth (Eichhornia crassipes), duckweed (Lemna minor), and Pistia stratiotes have demonstrated high efficiency in absorbing and concentrating metals like lead, cadmium, chromium, copper, nickel, and zinc from aqueous solutions, with some species able to concentrate metals hundreds of times above the initial water concentrations (Dushenkov et al., 1995; Singh et al., 2025; Rezania et al., 2016; Galal et al., 2018; Karkhanis , 2006). The process involves both absorption into root tissues and root-mediated precipitation of metals, with live roots being significantly more effective than dried ones (Dushenkov et al., 1995). Mixed cultures of macrophytes in constructed wetlands can achieve removal rates of up to 98–99% for several metals within days, and free-floating plants generally outperform submerged or emergent species due to their morphology and rapid growth (Singh et al., 2025; Rezania et al., 2016). The effectiveness of rhizofiltration depends on factors such as plant species, water pH, temperature, and metal concentration, and requires regular harvesting and safe disposal of contaminated biomass to prevent secondary pollution (Bakshe and Jugade , 2023; Rezania et al., 2016; Galal et al., 2018). Recent research also highlights the potential for enhancing rhizofiltration through the use of plant growth-promoting rhizobacteria and genetic engineering to improve metal uptake and tolerance (Lal et al., 2018; Rawat et al., 2012; Xing et al., 2022). Rhizofiltration is effective in treating wastewater and runoff but requires the regular harvesting of root biomass and safe disposal of contaminated plant material. It is a promising green technology for mitigating heavy metal pollution in water bodies, especially in industrial and urban settings (Kanwar et al., 2020).

4. Phytovolatilization

Phytovolatilization is a phytoremediation strategy where plants absorb metals and metalloids, transform them into volatile forms, and release them into the atmosphere, most notably with elements like mercury and selenium. Species such as Brassica and Liriodendron have shown the ability to volatilize selenium, while Arabidopsis thaliana can volatilize mercury, especially when genetically engineered to express specific enzymes that facilitate this transformation. Advances in genetic engineering have enhanced the efficiency of phytovolatilization by introducing genes for metal transporters, sulfur metabolism enzymes, and bacterial enzymes like mercuric reductase, enabling plants to convert toxic ions into less harmful volatile forms that are released through transpiration (Kotrba, et al., 2009; LeDuc and Terry, 2005; Chaney, et al., 1997).

This approach offers a cost-effective and eco-friendly method to reduce soil and water contamination, but concerns remain about the environmental safety of releasing transformed contaminants into the atmosphere, even in less toxic or trace forms (Muthusaravanan et al., 2018; Marques et al., 2009; Shen et al., 2022). The long-term ecological impacts, including potential atmospheric redistribution and re-deposition of these elements, are not fully understood and require further research (Pathak et al., 2020; Rai et al., 2021). Despite these uncertainties, phytovolatilization remains a promising tool, especially when combined with other remediation strategies and careful site-specific management (Susarla et al., 2002; Kumar et al., 2023).

Phytotransformation is a key phytoremediation mechanism in which plants enzymatically degrade, metabolize, or chemically modify organic pollutants, such as pesticides, hydrocarbons, and industrial chemicals, into less toxic forms. This process occurs within plant tissues or in the rhizosphere, often involving enzymes like dehalogenases, peroxidases, and laccases, and is sometimes enhanced by plant-associated microbes that further break down contaminants (Singh and Singh, 2017; Susarla et al., 2002; Kafle et al., 2022). Studies have shown that aquatic plants like duckweed and elodea can effectively transform persistent organic pollutants such as DDT into less harmful metabolites, primarily through reductive dechlorination pathways (Gao et al., 2000).

The efficiency of phytotransformation can be increased by leveraging plant-microbe partnerships, particularly with endophytic bacteria that possess pollutant-degrading capabilities and promote plant growth under stress (Afzal et al., 2014; Xiang et al., 2022). Additionally, integrating amendments like biochar can support beneficial microbial communities and improve soil conditions, further enhancing the breakdown of organic contaminants (Wiszniewska et al., 2016). Advances in genetic engineering and the use of transgenic plants are also being explored to boost the enzymatic capacity for phytotransformation (Singh and Singh, 2017; Kafle et al., 2022). phytotransformation offers a sustainable, in situ solution for detoxifying sites contaminated with complex mixtures of organic pollutants, with the added benefits of being cost-effective and environmentally friendly compared to conventional remediation methods (Latif et al., 2023).

Phytodegradation is a process in which plants enzymatically break down organic pollutants, such as pesticides, hydrocarbons, solvents, and explosives, into less toxic or non-toxic compounds within their tissues or in the rhizosphere, the soil region influenced by roots. This breakdown is facilitated by plant enzymes like peroxidases, laccases, and dehalogenases, which transform complex contaminants into simpler, often less harmful molecules. Some of these by-products may be incorporated into plant biomass, while others are released back into the environment in safer forms. The efficiency of phytodegradation can be enhanced by the presence of endophytic bacteria within plant tissues, which possess their own metabolic pathways for degrading persistent organic pollutants and can promote plant growth, further boosting remediation effectiveness (Newman and Reynolds, 2004; Chlebek and Hupert-Kocurek, 2019).

Phytodegradation is distinct from other phytoremediation mechanisms because it involves actual chemical transformation of pollutants, rather than just uptake or immobilization. This method is particularly advantageous for remediating soils and waters contaminated with biodegradable organic compounds, offering a cost-effective and environmentally friendly alternative to traditional remediation techniques. However, the success of phytodegradation depends on factors such as the type of contaminant, plant species, soil conditions, and the presence of supportive microbial communities, and it may require years for complete cleanup in some cases (Schwitzguébel , 2017; Trapp and Karlson , 2001; Khan et al., 2023; Meagher , 2000).

III. PLANT SPECIES UTILIZED IN PHYTOREMEDIATION AND THEIR TARGET HEAVY METALS

Table 3 presents a curated list of plant species commonly used in phytoremediation, with particular emphasis on those identified in both tropical regions such as Nigeria and temperate zones globally. The table outlines the botanical identity and growth habit of each plant—whether herbaceous, shrubby, or tree-like, alongside the specific heavy metals they are known to remediate, the mechanism of phytoremediation they employ (e.g., phytoextraction, phytostabilization, or rhizofiltration), and supporting scientific references.

Table 3: Documented Plant Species Used for Phytoremediation in Tropical and Temperate Regions, Their Heavy Metal Targets, Remediation Roles, and References

s/n	Plant (Region / Habit)	Metals Removed	Role (Phytoextraction / Stabilization / Rhizofiltration)	References
1.	Calotropis procera (shrub, Nigeria)	Cromium (Cr), Arsenic (Ar)	Phytoextraction (hyperaccumulator)	Usman *et al.* 2020; Singh and Fulzele , 2021; Kanwar *et al.* 2023
2.	Azadirachta indica, , (trees, Nigeria)	lead (Pb), zinc (Zn), cadmium (Cd), copper (Cu), nickel (Ni), and iron (Fe), Nickel (Ni)	Phytoextraction	Tiwari *et al.* 2017; Colona *et al.* 2018
3.	Brassica juncea (Indian mustard)	cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), and mercury (Hg)	Phytoextraction	Qadir *et al.* 2004; Goswami and Das,2015; Gurajala *et al.* 2019

4.	Helianthus annuus (Sunflower)-Herbs/Tithonia diversifolia-shrub (Mexican Sunflower)	lead (Pb), cadmium (Cd), and zinc (Zn)	Phytoextraction	Adewole *et al.* 2009; Adesodun *et al.* 2010; Adewole *et al.,* 2010; Paulo *et al.* 2023
5.	Eucalyptus camaldulensis (trees, Nigeria)	Lead (Pb), cadmium (Cd), arsenic (As), and zinc (Zn).	Phytostabilization/ Phytoextraction	Madejon *et al.,* 2017; Al-Salmany and Ibrahim, 2021
6.	Vitellaria paradoxa - shea butter tree (trees, Nigeria)	pollutants from pharmaceutical effluents	Phytoextraction	Ramirez Sandoval , 2013; Ojo *et al.* 2021
7.	Ocimum basilicum (herb, Nigeria)	cadmium (Cd) lead (Pb), organic pollutants such as the pesticide endosulfan	Phytoextraction (root hyperaccumulation)	Youssef, 2021; Ismaiel , 2021; Shehu *et al.* 2023.
8.	Chromolaena odorata (weed, Nigeria)	cadmium (Cd) , lead (Pb), total petroleum hydrocarbons (TPH) and PCBs in oil-contaminated soils	Phytoextraction	Jampasri *et al.* 2021; Anyasi and Atagana, 2021
9.	Cynodon dactylon - Bermuda grass (grass, Nigeria)	Cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn), iron (Fe), PAHs and crude oil in contaminated soils	Phytostabilization (roots) and Phytoextraction (Fe)	Raimi and Isichei, 2015; Shuaibu *et al.* 2021; Song *et al.* 2022; Mohammed *et al.* 2024
10.	Solanum melongena – (eggpla	cadmium (Cd), lead (Pb),	Phytoextraction	Yashim *et al.* 2014

	nt) (edible plants, Nigeria)	and manganese (Mn)		
11.	Rumex acetosa (edible plants, Nigeria)	Copper (Cu)r, lead (Pb), zinc (Zn), cadmium (Cd), and even radiocesium	Phytoextraction	Barrutia *et al.* 2009; Yashim *et al.*, 2014; He *et al.* 2024
12.	Lycopersicon esculentum (Tomato)-(edible plants, Nigeria)	Copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni)	Phytoextraction	Harikishan and Kumar, 2010; Andal *et al.* 2014; Devi, *et al.* 2024
13.	Sorghum bicolor (crop, Nigeria)	Cadmium (Cd), lead (Pb), nickel (Ni), zinc (Zn), copper (Cu),	Phytoextraction / Rhizofiltration	Al Chami *et al.* 2015; Phieler *et al.* 2015; Jia *et al.* 2016 Silamb
		and strontium (St),		arasan *et al.* 2023
14.	Glycine max (soybean, Nigeria)	Cadmium (Cd), lead (Pb), copper (Cu), chromium (Cr), nickel (Ni), and zinc (Zn)	Phytoextraction/Phytostabilization	Rojjanateeranaj *et al.* 2017; Bilal *et al.* 2017; Hussain *et al.* 2019; Adeyemi,*et al.*, 2021
15.	Senna alata (shrub, Nigeria)	Lead (Pb), nickel (Ni), chromium (Cr), cadmium (Cd), copper (Cu), zinc (Zn), iron (Fe), and aluminum (Al)	Phytoextraction (bioaccumulation)	Emmanuel *et al.*, 2019; Njoku and Jolaoso, 2020;
16.	Hyptis suaveolens, (weeds, Nigeria)	Chromiun (Cr)	Phytoextraction / Rhizofilteration	Sivakumar *et al.* 2016;
17.	Urena lobata (weeds, Nigeria)	Arsenic (Ar), cadmium	Phytoextraction	Chidi *et al.* 2021

		(Cd), lead (Pb), and chromium (Cr) ,		
18.	Vernonia ambigua (weeds, Nigeria)	zinc (Zn), lead (Pb), and copper (Cu)	Phytoextraction	Akomolafe and Lawal, 2019
19.	Panicum maximum- Guinea grass (tropical herbs)	can remove 74–99% of alkanes and up to 90% of polycyclic aromatic hydrocarbons (PAHs) from oil-contaminated soils within 112 days	Phytoextraction / Rhizofiltration	Rodriguez-Campos *et al.* 2019; Ochekwu *et al.* 2020; Okonofua and Kayode-Ojo, 2021
20.	Zea mays (tropical herbs)	Lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni)	Phytoextraction / Phytostabilization	Singh *et al.* 2019; Menhas *et al.* 2021; Vishnupradeep *et al.*, 2022; Adejumo *et al.* 2023
21.	Vetiveria zizanioides- vetiver grass - (tropical herbs)	Lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (Ar)	Phytoextraction / Phytostabilization	Danh *et al.* 2009; Phusantisampan *et al.* 2016; Nayak *et al.* 2018
22.	Pteris vittata- Chinese brake fern (fern), temperate/tropical)	Arsenic (As) (up to 22,630 ppm in fronds), and others like cadmium (Cd) and zinc (Zn)	Phytoextraction (hyperaccumulator)	An *et al.* 2006; Xiyuan *et al.* 2008; Danh *et al.* 2014; Cantamessa *et al.* 2020
23.	Thlaspi caerulescens. (pennycress, temperate)	zinc (Zn), cadmium (Cd), and sometimes lead (Pb) and nickel (Ni)	Phytoextraction (hyperaccumulators)	Robinson *et al.* 1998; Escarré *et al.* 2000; Milner and Kochian, 2008

24.	Azolla pinnata, (aquatic, tropical)	chromium (Cr), cadmium (Cd), lead (Pb), and, to a lesser extent, nickel (Ni)	Rhizofiltration / Phytoextraction	Rai *et al.* 2009; Lokuge, 2016; Kumar *et al.* 2020
25.	Eichhornia crassipes- water hyacinth (aquatic, tropical)	remove phenol and cyanide from waste water, can also remove chromium (Cr), copper (Cu), cadmium (Cd), and lead (Pb)	Rhizofiltration / Phytoextraction	Ting *et al.* 2018; Tabinda *et al.* 2020; Singh and Balomajumder, 2021; Rasool *et al.,* 2023

IV. CASE STUDIES OF HEAVY METAL POLLUTION IN NIGERIA

Zamfara Lead Poisoning Crisis (2010–Present): Artisanal gold mining in Zamfara resulted in widespread lead contamination, leading to the death of over 400 children and long-term health effects in thousands of residents, highlighting the dangers of artisanal and small-scale mining when safety and environmental regulations are lacking (Schwartz et al., 2021). In addition to chemical hazards, mining communities face physical dangers from accidents, overexertion, and poor working conditions, as well as social challenges like poverty, lack of healthcare, and inadequate compensation for injuries or illness (Sahoo and Rout, 2023; Stewart, 2020). Radioactive elements and particulate matter released during mining further elevate long-term cancer risks and other health issues (Owusu et al., 2024; Otorkpa et al., 2024).

Niger Delta Oil Spill Pollution: Studies have shown that heavy metals from crude oil spills in Bayelsa, Delta and Rivers States have contaminated farmland and water bodies, affecting local livelihoods and increasing cancer risks. The oil-rich Niger Delta is perhaps the most polluted region in Nigeria, suffering from years of unchecked petroleum exploration, frequent oil spills, and gas flaring. Soils and water bodies in these states have been shown to contain excessive levels of lead, cadmium, and nickel (Nduka and Orisakwe, 2011; Onyena et al., 2024). Seafood sourced from these waters also accumulates these toxic metals, posing risks to consumers, particularly in communities where fish is a dietary staple. Some soil samples in the region contain up to 895 mg/kg of lead, nearly 45 times the WHO limit (Olawoyin et al., 2012). Despite localized remediation efforts, persistent pollution and inadequate regulatory oversight have made these regions environmental sacrifice zones. Long-term health effects include liver and kidney dysfunction, birth defects, and increased cancer incidence. The socioeconomic implications are equally severe: contaminated farmlands and waters have diminished local livelihoods, deepened poverty, and fueled conflict over environmental justice.

Kano Industrial Pollution: Industrial pollution in Kano, Nigeria, is a significant environmental and public health concern, primarily due to the discharge of untreated industrial effluents into rivers and the atmosphere. Studies have found that rivers such as Challawa and Salanta, which receive waste from major industrial estates, contain high levels of heavy metals (including cadmium, chromium, lead, and iron) and other pollutants, often exceeding both Nigerian and World Health Organization safety limits for drinking and irrigation water, posing risks to water supplies and agriculture. Groundwater in industrial areas also shows contamination, with cadmium particularly prevalent, and pollution indices categorizing some zones as seriously polluted. Air quality assessments reveal elevated concentrations of gaseous pollutants like carbon monoxide and nitrogen dioxide near industrial stacks, with some CO levels surpassing recommended limits, especially under certain atmospheric conditions (Dan'azumi and Bichi, 2010; Hamidu et al., 2021; Oji and Adamu, 2021). Lead and chromium are also frequently found at hazardous levels, contributing to ecological and human health risks (Sivarajah et al., 2024). In addition, vanadium and titanium, though less studied, have been detected in mining areas and are recognized as emerging contaminants with potential health impacts1(Tiemoko et al., 2024). The migration of these metals from tailings into surrounding soils and water bodies occurs through processes like runoff, leaching, and atmospheric transport, leading to persistent environmental contamination (Chen et al., 2023). Biomonitoring studies confirm that people living or working near gold mines often have higher internal levels of these metals, underscoring the need for ongoing health surveillance and environmental remediation (Diarra et al., 2024).

Gold mining in Osun and Zamfara: Gold mining in regions such as Osun, Zamfara, and Niger has been linked to significant contamination of water, soil, and sediments with toxic metals like arsenic, lead, chromium, vanadium, and titanium. Studies from various gold mining areas globally have consistently found elevated concentrations of these metals in mining wastes, tailings, and surrounding environments, often exceeding recommended safety thresholds and posing direct health risks to local communities through exposure pathways such as water, soil, and food chains (Odumo et al., 2011; de Souza Neto et al., 2020; Baneh et al., 2024). For example, arsenic levels in mining tailings and soils can reach thousands of milligrams per kilogram, far above environmental safety limits, and are associated with increased cancer risks and other health problems in both adults and children (Eisler, 2003; Wongsasuluk et al., 2021).

V. RECOMMENDATIONS FOR SUSTAINABLE ENVIRONMENTAL

Remediation and Public Health Protection in Nigeria Given the escalating challenges posed by heavy metal contamination from mining, industrial emissions, and unsafe agricultural practices, the following actionable recommendations are proposed for government authorities, environmental regulators, health institutions, and stakeholders in Nigeria:

Adopt phytoremediation as a national strategy for environmental clean-up:The government and stakeholders are strongly encouraged to integrate phytoremediation into national and regional environmental remediation programs. Phytoremediation is a low-cost, eco-friendly, and sustainable technology that uses plants to extract, stabilize, or degrade toxic heavy metals from soil and water. Indigenous and naturalized plant species such as Tithonia diversifolia, Chromolaena odorata, Helianthus annuus, and Vetiveria zizanioides have already demonstrated effectiveness in Nigerian contexts.

Strengthen Environmental Regulations on Mining and Industrial Activities

Unregulated mining continues to endanger public health, especially among children and vulnerable populations exposed to lead, arsenic, cadmium, and mercury. Government agencies must strictly enforce environmental protection laws, mandate Environmental Impact Assessments (EIAs), and penalize non-compliance. Regular environmental audits and soil/water testing should be compulsory near mining and industrial sites.

Promote community based phytoremediation programmes: Community-led clean-up initiatives, supported by environmental NGOs and local governments, should be launched in areas impacted by artisanal mining and industrial discharges. These programs should train residents in planting and maintaining phytoremediation species, thereby creating jobs and enhancing public participation in environmental health.

Regulate and Monitor Agricultural Inputs to Reduce Heavy Metal Accumulation in Food Crops

Fertilizers, pesticides, and irrigation water should be strictly monitored for heavy metal content. Farmers should be educated on the dangers of cultivating crops near industrial zones and encouraged to use phytoremediation plants in buffer zones to reduce soil toxicity. Regulatory frameworks should align with international food safety standards (FAO/WHO). Establish phytoremediation research and demonstration centres: Investment should be directed toward research institutes and universities to develop region-specific phytoremediation protocols. Demonstration sites across geopolitical zones can serve as practical learning grounds for students, professionals, and policymakers.

Integrate environmental health surveillance into public health systems: Routine screening for heavy metal exposure should be integrated into health services in high-risk areas. Early detection programs, particularly targeting children and pregnant women, are critical to prevent long-term health consequences.

Encourage cross-sector collaboration and international partnerships: Collaboration between ministries of environment, health, agriculture, and education, as well as international organizations, will ensure coordinated efforts. Funding from international development agencies can also support phytoremediation initiatives and environmental restoration projects.

VI. CONCLUSION

A paradigm shift toward sustainable, nature-based solutions such as phytoremediation is essential in mitigating the toxic legacy of mining, industrialization, and unsafe agricultural practices. With strong political will, institutional support, and community involvement, Nigeria can protect its ecosystems, safeguard public health, and ensure food and water safety for future generations.

REFERENCES

1. Adekiya, A. O., Oloruntoba, A., Ewulo, B. S., Ogunbode, T., and Sangoyomi, T. (2024). Heavy metal pollution in soils near Ilesha gold mining area, Nigeria. The Open Agriculture Journal, 18(1).
2. Adejumo, A. L., Azeez, L., Kolawole, T. O., Aremu, H. K., Adedotun, I. S., Oladeji, R. D., .. and Abdullah, M. (2023). Silver nanoparticles strengthen Zea mays against toxic metal-related phytotoxicity via enhanced metal phytostabilization and improved antioxidant responses. International Journal of Phytoremediation, 25(12), 1676-1686.
3. Adesodun, J. K., Atayese, M. O., Agbaje, T. A., Osadiaye, B. A., Mafe, O. F., and Soretire, A. A. (2010). Phytoremediation potentials of sunflowers (Tithonia diversifolia and Helianthus annuus) for metals in soils contaminated with zinc and lead nitrates. Water, air, and soil pollution, 207, 195-201.
4. Adewole, M. B., Adeoye, G. O., and Sridhar, M. K. C. (2009). Effect of seasonal variation on the removal of Pb and Cd from a polluted field using Helianthus annuus L. and Tithonia diversifolia (Hemsl.). Toxicological and environmental chemistry, 91(5), 923-931.
5. Adewole, M. B., Sridhar, M. K. C., and Adeoye, G. O. (2010). Removal of heavy metals from soil polluted with effluents from a paint industry using Helianthus annuus L. and Tithonia diversifolia (Hemsl.) as influenced by fertilizer applications. Bioremediation Journal, 14(4), 169-179.
6. Adewumi, A. J., and Laniyan, T. A. (2023). Contamination, ecological, and human health risks of heavy metals in water from a Pb–Zn–F mining area, North Eastern Nigeria. Journal of Water and Health, 21(10), 1470-1488.
7. Adeyemi, N. O., Atayese, M. O., Sakariyawo, O. S., Azeez, J. O., Sobowale, S. P. A., Olubode, A., ... and Adeoye, S. (2021). Alleviation of heavy metal stress by arbuscular mycorrhizal symbiosis in Glycine max (L.) grown in copper, lead and zinc contaminated
8. Adeyemi, A. A., and Ojekunle, Z. O. (2021). Concentrations and health risk assessment of

industrial heavy metals pollution in groundwater in Ogun state, Nigeria. Scientific African, 11, e00666.

9. Adimalla, N., Chen, J., and Qian, H. (2020). Spatial characteristics of heavy metal contamination and potential human health risk assessment of urban soils: A case study from an urban region of South India. Ecotoxicology and environmental safety, 194, 110406.
10. Afzal, M., Khan, Q. M., and Sessitsch, A. (2014). Endophytic bacteria: prospects and applications for the phytoremediation of organic pollutants. Chemosphere, 117, 232-242.
11. Akindele, E. O., Oladeji, T. A., Kowobari, E. D., Adedapo, A. M., Fagbohun, I. R., Akinpelu, O. T., and Oyeku, O. G. (2023). Gold mining impairs the biological water quality of a culturally important river and UNESCO World Heritage Site in Nigeria. Environmental pollution, 326, 121470.
12. Akinnifesi, O., Adesina, F., Ogunwole, G., and Abiya, S. (2021). Occurrence and impact of heavy metals on some water, land, flora and fauna resources across Southwestern Nigeria. In Heavy Metals-Their Environmental Impacts and Mitigation. IntechOpen.
13. Akinwumi, I. A., Adegoke, S. A., Oyelami, O. A., Akinwumi, A. E., and Adedeji, T. A. (2023). High blood lead levels of children in a gold mining community in Osun State, Nigeria: an urgent call for action. Transactions of The Royal Society of Tropical Medicine and Hygiene, 117(10), 714-726.
14. Akomolafe, G. F., and Lawal, S. (2019). Heavy metal accumulation in some plants growing at polluted soils in Lafia, Nigeria. FUDMA Journal of Sciences, 3(2), 9-14.
15. Ali, H., Khan, E., and Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. Journal of chemistry, 2019(1), 6730305.
16. Al Chami, Z., Amer, N., Al Bitar, L., and Cavoski, I. (2015). Potential use of Sorghum bicolor and Carthamus tinctorius in phytoremediation of nickel, lead and zinc. International journal of environmental science and technology, 12, 3957-3970.
17. Al-Salmany, S. W. K., and Ibrahim, I. A. (2021). Phytoextraction of cadmium and lead from a contaminated soil using Eucalyptus seedlings. Iraqi Journal of Agricultural Sciences, 52(4).
18. Andal, F. A., and Ching, J. A. (2014, March). Phytoremediation potential of Tomato (Lycopersicon esculentum Mill) in artificially contaminated soils. In DLSU Research Congress Proceedings.
19. An, Z. Z., Huang, Z. C., Lei, M., Liao, X. Y., Zheng, Y. M., and Chen, T. B. (2006). Zinc tolerance and accumulation in Pteris vittata L. and its potential for phytoremediation of Zn-and As-contaminated soil. Chemosphere, 62(5), 796-802.
20. Anyasi, R. O., and Atagana, H. I. (2021). Understanding the effect of oil on phytoremediation of PCB co-contamination in transformer oil using Chromolaena odorata. International Journal of Phytoremediation, 23(6), 597-608.
21. Ashraf, S., Ali, Q., Zahir, Z. A., Ashraf, S., and Asghar, H. N. (2019). Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. Ecotoxicology and environmental safety, 174, 714-727.
22. Awoyelu, F. E., and Mebo, R. A. (2022). Effects of sand mining on peri-urban agriculture in Ife East and Ife Central Local Government Areas, Osun State, Nigeria. Agro-Science, 21(3), 101-107.
23. Aziz, R. A., Yiwen, M., Saleh, M., Salleh, M. N., Gopinath, S. C., Giap, S. G. E., ... and Gobinath, R. (2023). Bioaccumulation and translocation of heavy metals in paddy (Oryza sativa L.) and soil in different land use practices. Sustainability, 15(18), 13426.
24. Badamasi, H., Hassan, U. F., and Adamu, H. M. (2022). Physico-chemical Properties and Heavy Metal Contamination Levels of Soils from Riruwai Mining Area, North-western Nigeria. Malaysian Journal of Applied Sciences, 7(2), 29-43.

25. Bakshe, P., and Jugade, R. (2023). Phytostabilization and rhizofiltration of toxic heavy metals by heavy metal accumulator plants for sustainable management of contaminated industrial sites: A comprehensive review. Journal of Hazardous Materials Advances, 10, 100293.
26. Barrutia, O., Epelde, L., García-Plazaola, J. I., Garbisu, C., and Becerril, J. M. (2009). Phytoextraction potential of two Rumex acetosa L. accessions collected from metalliferous and non-metalliferous sites: Effect of fertilization. Chemosphere, 74(2), 259-264.
27. Bawa-Allah, K. A. (2023). Assessment of heavy metal pollution in Nigerian surface freshwaters and sediment: A meta-analysis using ecological and human health risk indices. Journal of Contaminant Hydrology, 256, 104199.
28. Bawa, U. (2023). Heavy metals concentration in food crops irrigated with pesticides and their associated human health risks in Paki, Kaduna State, Nigeria. Cogent Food and Agriculture, 9(1), 2191889.
29. Bilal, S., Khan, A. L., Shahzad, R., Asaf, S., Kang, S. M., and Lee, I. J. (2017). Endophytic Paecilomyces formosus LHL10 augments Glycine max L. adaptation to Ni-contamination through affecting endogenous phytohormones and oxidative stress. Frontiers in plant nscience, 8, 870.
30. Bishnu Agnon, P., Islam, S., KC, S., Das, A., Anjum, N., Poudel, A., and Akter Suchi, S. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain.
31. Cantamessa, S., Massa, N., Gamalero, E., and Berta, G. (2020). Phytoremediation of a highly arsenic polluted site, using Pteris vittata L. and arbuscular mycorrhizal fungi. Plants, 9(9), 1211.
32. Castro, S., Davis, L. C., and Erickson, L. E. (2003). Phytotransformation of benzotriazoles. International Journal of Phytoremediation, 5(3), 245-265.
33. Chaney, R. L., Angle, J. S., Broadhurst, C. L., Peters, C. A., Tappero, R. V., and Sparks, D. L. (2007). Improved understanding of hyperaccumulation yields commercial phytoextraction and phytomining technologies. Journal of Environmental Quality, 36(5), 1429-1443.
34. Chaney, R. L., Malik, M., Li, Y. M., Brown, S. L., Brewer, E. P., Angle, J. S., and Baker, A. J. (1997). Phytoremediation of soil metals. Current opinion in Biotechnology, 8(3), 279-284.
35. Chen, Y., Liu, G., Zhou, C., Zhou, H., Wei, Y., and Liu, Y. (2023). The influence of gold mining wastes on the migration-transformation behavior and health risks of arsenic in the surrounding soil of mined-area. Frontiers in Earth Science, 10, 1068763.
36. Cheraghi, M., Lorestani, B., Khorasani, N., Yousefi, N., and Karami, M. (2011). Findings on the phytoextraction and phytostabilization of soils contaminated with heavy metals. Biological Trace Element Research, 144, 1133-1141.
37. Chidi, O., Uzoma, A., Okwoli, A., Tereze, A., and Joseph, O. (2021). Efficacy of Urena lobata in Phytoremediation of Spent Engine Oil Polluted Soil. American Journal of Environment Studies. https://doi.org/10.47672/ajes.807.
38. Chlebek, D., and Hupert-Kocurek, K. (2019). BAKTERIE ENDOFITYCZNE W FITODEGRADACJI TOKSYCZNYCH ZANIECZYSZCZEŃ ORGANICZNYCH. Advancements of Microbiology, 58(1).
39. Chinedu, E., and Chukwuemeka, C. K. (2018). Oil spillage and heavy metals toxicity risk in the Niger Delta, Nigeria. Journal of Health and Pollution, 8(19), 180905.
40. Chris, D. I., Onyena, A. P., and Sam, K. (2023). Evaluation of human health and ecological risk of heavy metals in water, sediment and shellfishes in typical artisanal oil mining areas of Nigeria. Environmental Science and Pollution Research, 30(33), 80055-80069.
41. Collina, K., Junior, F., Nnamdi, N., and Janfa, N. (2018). Comparative studies on the efficacy of Azadirachta indica and Moringa oleifera in phytoremediation of some selected heavy metals from contaminated soil. Asian J Environ Ecol, 5, 1-11

42. Dan'azumi, S., and Bichi, M. H. (2010). Industrial pollution and implication on source of water supply in Kano, Nigeria. International Journal of Engineering and Technology, 10(1), 101-109.
43. Danh, L. T., Truong, P., Mammucari, R., Tran, T., and Foster, N. (2009). Vetiver grass, Vetiveria zizanioides: a choice plant for phytoremediation of heavy metals and organic wastes. International journal of phytoremediation, 11(8), 664-691.
44. Darma, A. I., Zakari, S. A., Sani, A., and Mamman, H. S. (2024). SOIL POLLUTION AND HEAVY METAL CONTAMINATION: INSIGHT FROM EFFLUENT DISCHARGED FROM CHALLAWA INDUSTRIAL AREA, NIGERIA. FUDMA JOURNAL OF SCIENCES, 8(6), 355-361.
45. de Souza, D. M., da Silva, J. D. L., Ludwig, L. D. C., Petersen, B. C., Brehm, F. A., Modolo, R. C. E., ... and Moraes, C. A. (2023). Study of the phytoremediation potential of native plant species identified in an area contaminated by volatile organic compounds: a systematic review. International Journal of Phytoremediation, 25(11), 1524-1541.
46. de Souza, V. B., Hollas, C. E., Bortoli, M., Manosso, F. C., and de Souza, D. Z. (2023). Heavy metal contamination in soils of a decommissioned landfill southern Brazil: Ecological and health risk assessment. Chemosphere, 339, 139689.
47. Devi, Y., Surendran, A., and Thatheyus, A. J. (2024). Phytoremediation of Copper Using the Tomato Plant, Lycopersicon esculentum. Research in Biotechnology and Environmental Science, 3(2), 23-28.
48. Diarra, Z., Dieme, D., and Bouchard, M. (2024). Biomonitoring of exposure to metals and metalloids using toenail and fingernail sampling in individuals from artisanal gold mining areas in Mali. Environmental Advances, 17, 100589.
49. Dushenkov, V., Kumar, P. N., Motto, H., and Raskin, I. (1995). Rhizofiltration: the use of plants to remove heavy metals from aqueous streams. Environmental science and technology, 29(5), 1239-1245.
50. Egbueri, J. C., Ukah, B. U., Ubido, O. E., and Unigwe, C. O. (2022). A chemometric approach to source apportionment, ecological and health risk assessment of heavy metals in industrial soils from southwestern Nigeria. International Journal of Environmental Analytical Chemistry, 102(14), 3399-3417.
51. Ejike, C. E., Eferibe, C. O., and Okonkwo, F. O. (2017). Concentrations of some heavy metals in underground water samples from a Nigerian crude oil producing community. Environmental Science and Pollution Research, 24, 8436-8442.
52. Emmanuel, C. U., Alfreda, O. N., and Benita, C. A. (2019). Phytoremediation of heavy metals in spent engine oil-polluted soil by Senna alata L. bioRxiv, 532887.
53. Escarré, J., Lefèbvre, C., Gruber, W., Leblanc, M., Lepart, J., Rivière, Y., and Delay, B. (2000). Zinc and cadmium hyperaccumulation by Thlaspi caerulescens from metalliferous and nonmetalliferous sites in the Mediterranean area: implications for phytoremediation. The New Phytologist, 145(3), 429-437.
54. Eyankware, M. O., Akakuru, O. C., Osisanya, W. O., Umayah, S. O., and Ukor, K. P. (2023). Assessment of heavy metal pollution on groundwater quality in the Niger Delta Region of Nigeria. Sustainable Water Resources Management, 9(6), 189.
55. Ezeh, H. N., and Chukwu, E. (2011). Small scale mining and heavy metals pollution of agricultural soils: The case of Ishiagu Mining District, South Eastern Nigeria. Journal of geology and mining research, 3(4), 87-104.
56. Folarin, G. M., Badmus, B. S., Akinyemi, O. D., Idowu, O. A., Oke, A. O., Omodele, T., and Badmus, G. O.(2023) Metal and Microbial Contamination in the Water Available for Agriculture in Selected Farm Settlements in Nigeria.
57. Galal, T. M., Eid, E. M., Dakhil, M. A., and Hassan, L. M. (2018). Bioaccumulation and rhizofiltration potential of Pistia stratiotes L. for mitigating water pollution in the Egyptian wetlands. International journal of phytoremediation, 20(5), 440-447.

58. Gao, J., Garrison, A. W., Hoehamer, C., Mazur, C. S., and Wolfe, N. L. (2000). Uptake and Phytotransformation of o, p ′-DDT and p, p ′-DDT by Axenically Cultivated Aquatic Plants. Journal of Agricultural and Food Chemistry, 48(12), 6121-6127.
59. George, D. S., Hart, A. I., and Osuji, L. C. (2021). Concentration of heavy metals and petroleum hydrocarbons in previously remediated sites in Niger Delta, Nigeria. Scientia Africana, 20(3), 53-72.
60. Gerhardt, K. E., Gerwing, P. D., and Greenberg, B. M. (2017). Opinion: Taking phytoremediation from proven technology to accepted practice. Plant Science, 256, 170-185.
61. Guerra Sierra, B. E., Muñoz Guerrero, J., and Sokolski, S. (2021). Phytoremediation of heavy metals in tropical soils an overview. Sustainability, 13(5), 2574.
62. Gurajala, H. K., Cao, X., Tang, L., Ramesh, T. M., Lu, M., and Yang, X. (2019). Comparative assessment of Indian mustard (Brassica juncea L.) genotypes for phytoremediation of Cd and Pb contaminated soils. Environmental Pollution, 254, 113085.
63. Goswami, S., and Das, S. (2015). A study on cadmium phytoremediation potential of Indian mustard, Brassica juncea. International journal of phytoremediation, 17(6), 583-588.
64. Hamidu, H., Halilu, F. B., Yerima, K. M., Garba, L. M., Suleiman, A. A., Kankara, A. I., and Abdullahi, I. M. (2021). Heavy metals pollution indexing, geospatial and statistical approaches of groundwater within Challawa and Sharada industrial areas, Kano City, North-Western Nigeria. SN Applied Sciences, 3(7), 690.
65. Harikishan, U., and Kumar, A. (2010). Bioaccumulation of cadmium and lead by Lycopersicum esculentum (L.): impact on uptake of nutritional elements. Asian Journal of Water, Environment and Pollution, 7(2), 97-101.
66. Hazratqulov, S., von Ahlefeldt, G., Liu, R., Bessler, H., Almuina-Villar, H., Dieguez-Alonso, A., and Engels, C. (2024). Processing Municipal Waste for Phytostabilization of Heavy Metal Contaminated Soils. Soil Systems, 8(4), 109.
67. He, K., Sun, Z., Hu, Y., Zeng, X., Yu, Z., and Cheng, H. (2017). Comparison of soil heavy metal pollution caused by e-waste recycling activities and traditional industrial operations. Environmental Science and Pollution Research, 24, 9387-9398.
68. He, M., Yin, H., Liu, Z., Luo, F., Zhao, X., Li, H., and Song, X. (2024). Root exudate–assisted phytoremediation of copper and lead contamination using Rumex acetosa L. and Rumex K-1. Ecotoxicology and Environmental Safety, 284, 117036.
69. Hoang, H. G., Chiang, C. F., Lin, C., Wu, C. Y., Lee, C. W., Cheruiyot, N. K., ... and Bui, X. T. (2021). Human health risk simulation and assessment of heavy metal contamination in a river affected by industrial activities. Environmental Pollution, 285, 117414.
70. Houessionon, M. K., Ouendo, E. M. D., Bouland, C., Takyi, S. A., Kedote, N. M., Fayomi, B., ... and Basu, N. (2021). Environmental heavy metal contamination from Electronic Waste (e-waste) recycling activities worldwide: A systematic review from 2005 to 2017. International journal of environmental research and public health, 18(7), 3517.
71. Hou, D., Wang, K., Liu, T., Wang, H., Lin, Z., Qian, J., ... and Tian, S. (2017). Unique rhizosphere micro-characteristics facilitate phytoextraction of multiple metals in soil by the hyperaccumulating plant Sedum alfredii. Environmental science and technology, 51(10), 5675-5684.
72. https://humanglemedia.com/How Illegal Mining Is Contributing To Local Conflicts In Nigeria/
73. Huang, R., Dong, M., Mao, P., Zhuang, P., Paz-Ferreiro, J., Li, Y., ... and Li, Z. (2020). Evaluation of phytoremediation potential of five Cd (hyper) accumulators in two Cd contaminated soils. Science of the total environment, 721, 137581.
74. Hussain, A., Kamran, M. A., Javed, M. T., Hayat, K., Farooq, M. A., Ali, N., ... and Chaudhary, H. J. (2019). Individual and combinatorial application of Kocuria rhizophila and citric acid on phytoextraction of multi-metal

contaminated soils by Glycine max L. Environmental and Experimental Botany, 159, 23-33.
75. Hussein, M., Yoneda, K., Mohd-Zaki, Z., Amir, A., and Othman, N. (2021). Heavy metals in leachate, impacted soils and natural soils of different landfills in Malaysia: An alarming threat. Chemosphere, 267, 128874.
76. Ismaiel, S. A. (2021). Role of EDTA on hyper accumulation of CD with different solubility by Ocimum basilicum (L.). Plant Archives (09725210), 21(1).
77. Izah, S. C., Bassey, S. E., and Ohimain, E. I. (2017). Geo-accumulation index, enrichment factor and quantification of contamination of heavy metals in soil receiving cassava mill effluents in a rural community in the Niger Delta region of Nigeria. Molecular Soil Biology,
78. Izah, S. C., Chakrabarty, N., and Srivastav, A. L. (2016). A review on heavy metal concentration in potable water sources in Nigeria: human health effects and mitigating measures. Exposure and health, 8, 285-304.
79. Jampasri, K., Saeng-Ngam, S., Larpkern, P., Jantasorn, A., and Kruatrachue, M. (2021). Phytoremediation potential of Chromolaena odorata, Impatiens patula, and Gynura pseudochina grown in cadmium-polluted soils. International Journal of Phytoremediation, 23(10), 1061-1066.
80. Jia, W., Lv, S., Feng, J., Li, J., Li, Y., and Li, S. (2016). Morphophysiological characteristic analysis demonstrated the potential of sweet sorghum (Sorghum bicolor (L.) Moench) in the phytoremediation of cadmium-contaminated soils. Environmental Science and Pollution Research, 23, 18823-18831.
81. Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., and Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. Environmental Advances, 8, 100203.
82. Kanwar, P., Kumar, M., and Srivastava, S. (2023). Investigation of phytoextraction and tolerance capacity of Calotropis procera for the detoxification of hexavalent chromium, nickel, and lead. Environmental Technology and Innovation, 32, 103238.
83. Kanwar, V. S., Sharma, A., Srivastav, A. L., and Rani, L. (2020). Phytoremediation of toxic metals present in soil and water environment: a critical review. Environmental Science and Pollution Research, 27, 44835-44860.
84. Khan, S., Masoodi, T. H., Pala, N. A., Murtaza, S., Mugloo, J. A., Sofi, P. A., ... and Kumar, A. (2023). Phytoremediation prospects for restoration of contamination in the natural ecosystems. Water, 15(8), 1498.
85. Kolawole, T. O., Laniyan, T. A., Bello, E. O., and Isibor, R. A. (2022). Assessment of some potentially harmful elements and their associated health risk in stream sediments of rural gold-mining communities in Southwestern Nigeria. Arabian Journal of Geosciences, 15(10), 941.
86. Kolawole, T. O., Olatunji, A. S., Jimoh, M. T., and Fajemila, O. T. (2018). Heavy metal contamination and ecological risk assessment in soils and sediments of an industrial area in Southwestern Nigeria. Journal of Health and Pollution, 8(19), 180906.
87. Kotrba, P., Najmanova, J., Macek, T., Ruml, T., and Mackova, M. (2009). Genetically modified plants in phytoremediation of heavy metal and metalloid soil and sediment pollution. Biotechnology advances, 27(6), 799-810.
88. Kumar, V., Kumar, P., Singh, J., and Kumar, P. (2020). Potential of water fern (Azolla pinnata R. Br.) in phytoremediation of integrated industrial effluent of SIIDCUL, Haridwar, India: removal of physicochemical and heavy metal pollutants. International journal of phytoremediation, 22(4), 392-403.
89. Kumar, D., Malik, S., Rani, R., Kumar, R., and Duhan, J. S. (2023). Behavior, risk, and bioremediation potential of heavy metals/metalloids in the soil system. Rendiconti Lincei. Scienze Fisiche e Naturali, 34(3), 809-831.
90. .Lal, S., Ratna, S., Said, O. B., and Kumar, R. (2018). Biosurfactant and exopolysaccharide-

assisted rhizobacterial technique for the remediation of heavy metal contaminated soil: An advancement in metal phytoremediation technology. Environmental Technology and Innovation, 10, 243-263.

91. Laoye, B., Olagbemide, P., Ogunnusi, T., and Akpor, O. (2025). Heavy Metal Contamination: Sources, Health Impacts, and Sustainable Mitigation Strategies with Insights from Nigerian Case Studies. F1000Research, 14, 134.
92. Latif, A., Abbas, A., Iqbal, J., Azeem, M., Asghar, W., Ullah, R., ... and Chen, Z. (2023). Remediation of environmental contaminants through phytotechnology. Water, Air, and Soil Pollution, 234(3), 139.
93. LeDuc, D. L., and Terry, N. (2005). Phytoremediation of toxic trace elements in soil and water. Journal of Industrial Microbiology and Biotechnology, 32(11-12), 514-520.
94. Li, Z., Ding, Y., Ke, X., Wu, L., and Christie, P. (2021). Enhancement by soil micro-arthropods of phytoextraction of metal-contaminated soils using a hyperaccumulator plant species. Plant and Soil, 464, 335-346.
95. Li, J. T., Gurajala, H. K., Wu, L. H., Van Der Ent, A., Qiu, R. L., Baker, A. J., ... and Shu, W. S. (2018). Hyperaccumulator plants from China: a synthesis of the current state of knowledge. Environmental science and technology, 52(21), 11980-11994.
96. Lin, H., Liu, C., Li, B., and Dong, Y. (2021). Trifolium repens L. regulated phytoremediation of heavy metal contaminated soil by promoting soil enzyme activities and beneficial rhizosphere associated microorganisms. Journal of Hazardous Materials, 402, 123829.
97. Liu, S., Yang, B., Liang, Y., Xiao, Y., and Fang, J. (2020). Prospect of phytoremediation combined with other approaches for remediation of heavy metal-polluted soils. Environmental Science and Pollution Research, 27, 16069-16085.
98. Lokuge, U. M. L. (2016). A study on the Phytoremediation Potential of Azolla pinnata under laboratory conditions. Journal of Tropical Forestry and Environment, 6(1).
99. Madejon, P., Maranon, T., Navarro-Fernandez, C. M., Dominguez, M. T., Alegre, J. M., Robinson, B., and Murillo, J. M. (2017). Potential of Eucalyptus camaldulensis for phytostabilization and biomonitoring of trace-element contaminated soils. PLoS One, 12(6), e0180240.
100. Mahar, A., Wang, P., Ali, A., Awasthi, M. K., Lahori, A. H., Wang, Q., ... and Zhang, Z. (2016). Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. Ecotoxicology and environmental safety, 126, 111-121.
101. Makinde, W. O., Oluyemi, E. A., and Olabanji, I. O. (2013). Assessing the impacts of gold mining assessing the impacts of gold mining operations on river sediments and water samples from ilesa west local government area ILESA West Local Government Area of Osun State, Nigeria. In E3S Web of Conferences (Vol. 1). EDP Sciences.
102. Marques, A. P., Rangel, A. O., and Castro, P. M. (2009). Remediation of heavy metal contaminated soils: phytoremediation as a potentially promising clean-up technology. Critical Reviews in Environmental Science and Technology, 39(8), 622-654.
103. Meagher, R. B. (2000). Phytoremediation of toxic elemental and organic pollutants. Current opinion in plant biology, 3(2), 153-162.
104. Menhas, S., Hayat, K., Niazi, N. K., Zhou, P., Amna, Bundschuh, J., ... and Chaudhary, H. J. (2021). Microbe-EDTA mediated approach in the phytoremediation of lead-contaminated soils using maize (Zea mays L.) plants. International Journal of Phytoremediation, 23(6), 585-596.
105. Milner, M. J., and Kochian, L. V. (2008). Investigating heavy-metal hyperaccumulation using Thlaspi caerulescens as a model system. Annals of botany, 102(1), 3-13.
106. Mocek-Płóciniak, A., Mencel, J., Zakrzewski, W., and Roszkowski, S. (2023). Phytoremediation as an effective remedy for removing trace elements from ecosystems. Plants, 12(8), 1653.

107. Mohammed, R., Al-Gburi, H. F., Alotaibi, M. F., Almuqati, N. S., Alsufyani, S. J., Almoiqli, M. S., ... and Alharbi, K. N. (2024). Bioaccumulation and translocation of radionuclides heavy metals in Cynodon dactylon: A phytoremediation approach in Al-Dora refinery. Journal of Radiation Research and Applied Sciences, 17(3), 100953.

108. Muthusaravanan, S., Sivarajasekar, N., Vivek, J. S., Paramasivan, T., Naushad, M., Prakashmaran, J., ... and Al-Duaij, O. K. (2018). Phytoremediation of heavy metals: mechanisms, methods and enhancements. Environmental chemistry letters, 16, 1339-1359.

109. Nagy, A., Magyar, T., Kiss, N. É., and Tamás, J. (2023). Composted sewage sludge utilization in phytostabilization of heavy metals contaminated soils. International Journal of Phytoremediation, 25(11), 1510-1523

110. Nayak, A. K., Panda, S. S., Basu, A., and Dhal, N. K. (2018). Enhancement of toxic Cr (VI), Fe, and other heavy metals phytoremediation by the synergistic combination of native Bacillus cereus strain and Vetiveria zizanioides L. International journal of phytoremediation, 20(7), 682-691.

111. Nduka, J. K., and Orisakwe, O. E. (2011). Water-quality issues in the Niger Delta of Nigeria: a look at heavy metal levels and some physicochemical properties. Environmental science and pollution research, 18, 237-246.

112. Newman, L. A., and Reynolds, C. M. (2004). Phytodegradation of organic compounds. Current opinion in Biotechnology, 15(3), 225-230.

113. Njoku, K. L., and JOLAOSO, A. O. (2020). Growth and ability of Senna alata in phytoremediation of soil contaminated with heavy metals. Notulae Scientia Biologicae, 12(2), 420-432. soils. Rhizosphere, 18, 100325.

114. Nyiramigisha, P. (2021). Harmful impacts of heavy metal contamination in the soil and crops grown around dumpsites. Reviews in Agricultural Science, 9, 271-282.

115. Obasi, P. N., and Akudinobi, B. B. (2020). Potential health risk and levels of heavy metals in water resources of lead–zinc mining communities of Abakaliki, southeast Nigeria. Applied Water Science, 10(7), 1-23.

116. Ochekwu, E., Akpheokhai, L., and S.E, A. (2020). PHYTOREMEDIATION POTENTIAL OF Eleusine indica (L.) Gaertn, Panicum maximum Jacquin AND Lablab purpureus L. IN A CRUDE OIL POLLUTED SOIL. , 08, 56- 62. https://doi.org/10.31364/scirj/v8.i4.2020.p0420764.

117. O'Donohue, B., Hiti-Bandaralage, J., Gleeson, M., O'Brien, C., Harvey, M. A., Van Der Ent, A., ... and Hayward, A. (2022). Tissue culture tools for selenium hyperaccumulator Neptunia amplexicaulis for development in phytoextraction. Natural Products and Bioprospecting, 12(1), 28.

118. Odumo, O. B., Mustapha, A. O., Patel, J. P., and Angeyo, H. K. (2011). Multielemental analysis of Migori (Southwest, Kenya) artisanal gold mine ores and sediments by EDX-ray fluorescence technique: implications of occupational exposure and environmental impact. Bulletin of environmental contamination and toxicology, 86, 484-489.

119. Ojo, O., Kengne, M. H., Fotsing, M. C., Mmutlane, E. M., and Ndinteh, D. T. (2021). Traditional uses, phytochemistry, pharmacology and other potential applications of Vitellaria paradoxa Gaertn.(Sapotaceae): A review. Arabian Journal of Chemistry, 14(7), 103213.

120. Okonkwo, S. I., Idakwo, S. O., and Ameh, E. G. (2021). Heavy metal contamination and ecological risk assessment of soils around the pegmatite mining sites at Olode area, Ibadan southwestern Nigeria. Environmental Nanotechnology, Monitoring and Management, 15, 100424.

121. Okonofua, E. S., and Kayode-Ojo, N. (2021). Remediation of hydrocarbon contaminated soil using selected tropical plants.

122. Olatunde, K. A., Sosanya, P. A., Bada, B. S., Ojekunle, Z. O., and Abdussalaam, S. A. (2020). Distribution and ecological risk

assessment of heavy metals in soils around a major cement factory, Ibese, Nigeria. Scientific African, 9, e00496.

123. Olawoyin, R., Oyewole, S. A., and Grayson, R. L. (2012). Potential risk effect from elevated levels of soil heavy metals on human health in the Niger delta. Ecotoxicology and environmental safety, 85, 120-130.

124. Oloruntoba, A., Omoniyi, A. O., Shittu, Z. A., Ajala, R. O., and Kolawole, S. A. (2024). Heavy metal contamination in soils, water, and food in nigeria from 2000–2019: A systematic review on methods, pollution level and policy implications. Water, Air, and Soil Pollution, 235(9), 586.

125. Olujimi, O. O., Oputu, O., Fatoki, O., Opatoyinbo, O. E., Aroyewun, O. A., and Baruani, J. (2015). Heavy metals speciation and human health risk assessment at an illegal gold mining site in Igun, Osun State, Nigeria. Journal of Health and Pollution, 5(8), 19-32.

126. Olumayowa Oluwasola, H., Oluoye, O., Mohammad Bashir, S., Odewole, O. A., Onyeka Abugu, H., Akpomie, K. G., ... and Aishatu Umar, M. (2023). Geochemical and health risk assessment of heavy metals concentration in soils around Oke-Ere mining area in Kogi State, Nigeria. International Journal of Environmental Analytical Chemistry, 103(3), 685-700.

127. Onyena, A. P., Folorunso, O. M., Nwanganga, N., Udom, G. J., Ekhator, O. C., Frazzoli, C., ... and Orisakwe, O. E. (2024). Engaging one health in heavy metal pollution in some selected Nigerian Niger delta cities. A Systematic review of pervasiveness, bioaccumulation and subduing environmental health challenges. Biological Trace Element Research, 202(4), 1356-1389.

128. Oji, S., and Adamu, H. (2021). Air Pollution Exposure Mapping by GIS in Kano Metropolitan Area. Pollution, 7 (1), 101–112.

129. Otorkpa, O. J., Alao, J. O., and Emmanuel, S. (2024). Environmental and Health Impacts of Unregulated Lithium Mining Practices: Lessons from Nigeria's Oil Industry. African Journal of Environment and Natural Science Research, 7(3), 1-4.

130. Oyebamiji, A. O., Olaolorun, O. A., Popoola, O. J., and Zafar, T. (2024). Assessment of heavy metal pollution in soils of Jebba Area, Nigeria: Concentrations, source analysis and implications for ecological and human health risks. Science of The Total Environment, 945, 173860.

131. Pathak, S., Agarwal, A. V., and Pandey, V. C. (2020). Phytoremediation—a holistic approach for remediation of heavy metals and metalloids. In Bioremediation of pollutants (pp. 3-16). Elsevier.

132. Paulo, A. M., Caetano, N. S., Castro, P. M., and Marques, A. P. (2023). Phytomanagement of Zn-and Cd-contaminated soil: Helianthus annuus biomass production and metal remediation abilities with plant-growth-promoting microbiota assistance. Soil Systems, 7(3), 69.

133. Phieler, R., Merten, D., Roth, M., Büchel, G., and Kothe, E. (2015). Phytoremediation using microbially mediated metal accumulation in Sorghum bicolor. Environmental Science and Pollution Research, 22, 19408-19416.

134. Phusantisampan, T., Meeinkuirt, W., Saengwilai, P., Pichtel, J., and Chaiyarat, R. (2016). Phytostabilization potential of two ecotypes of Vetiveria zizanioides in cadmium-contaminated soils: greenhouse and field experiments. Environmental Science and Pollution Research, 23, 20027-20038.

135. Qadir, S., Qureshi, M. I., Javed, S., and Abdin, M. Z. (2004). Genotypic variation in phytoremediation potential of Brassica juncea cultivars exposed to Cd stress. Plant Science, 167(5), 1171-1181.

136. Rahman, M. S., Khan, M. D. H., Jolly, Y. N., Kabir, J., Akter, S., and Salam, A. (2019). Assessing risk to human health for heavy metal contamination through street dust in the Southeast Asian Megacity: Dhaka, Bangladesh. Science of the total environment, 660, 1610-1622.

137. Rai, P. K. (2009). Microcosm investigation on phytoremediation of Cr using Azolla pinnata.

International journal of phytoremediation, 12(1), 96-104.

138. Rai, G. K., Bhat, B. A., Mushtaq, M., Tariq, L., Rai, P. K., Basu, U., ... and Bhat, J. A. (2021). Insights into decontamination of soils by phytoremediation: A detailed account on heavy metal toxicity and mitigation strategies. Physiologia Plantarum, 173(1), 287-304.

139. Raimi, I. O., and Isichei, A. O. (2015). Bioaccumulation Potential of Cynodon dactylon Linn. In Crude Oil Contaminated Soil. Journal of Tropical Biology and Conservation (JTBC), 12.

140. RAMIREZ SANDOVAL, M. A. R. I. C. E. L. A. (2013). EFECTO DEL ENDOSULFAN SOBRE LA ACTIVIDAD DE GLUTATION S-TRANSFERASA DE OCIMUM BASILICUM L. CONACYT.

141. Rasool, S., Ahmad, I., Jamal, A., Saeed, M. F., Zakir, A., Abbas, G., ... and Caballero-Calvo, A. (2023). Evaluation of phytoremediation potential of an aquatic macrophyte (Eichhornia crassipes) in wastewater treatment. Sustainability, 15(15), 11533.

142. Rawat, K., Fulekar, M. H., and Pathak, B. (2012). Rhizofiltration: a green technology for remediation of heavy metals. Intl J Inno Biosci, 2(4), 193-199.

143. Rezania, S., Taib, S. M., Din, M. F. M., Dahalan, F. A., and Kamyab, H. (2016). Comprehensive review on phytotechnology: heavy metals removal by diverse aquatic plants species from wastewater. Journal of hazardous materials, 318, 587-599.

144. Robinson, B. H., Leblanc, M., Petit, D., Brooks, R. R., Kirkman, J. H., and Gregg, P. E. (1998). The potential of Thlaspi caerulescens for phytoremediation of contaminated soils. Plant and soil, 203, 47-56.

145. Rodriguez-Campos, J., Perales-Garcia, A., Hernandez-Carballo, J., Martinez-Rabelo, F., Hernández-Castellanos, B., Barois, I., and Contreras-Ramos, S. M. (2019). Bioremediation of soil contaminated by hydrocarbons with the combination of three technologies: bioaugmentation, phytoremediation, and vermiremediation. Journal of soils and sediments, 19, 1981-1994.

146. Rojjanateeranaj, P., Sangthong, C., and Prapagdee, B. (2017). Enhanced cadmium phytoremediation of Glycine max L. through bioaugmentation of cadmium-resistant bacteria assisted by biostimulation. Chemosphere, 185, 764-771.

147. Sabreena, Hassan, S., Bhat, S. A., Kumar, V., Ganai, B. A., and Ameen, F. (2022). Phytoremediation of heavy metals: an indispensable contrivance in green remediation technology. Plants, 11(9), 1255.

148. Sagbara, G., Zabbey, N., Sam, K., and Nwipie, G. N. (2020). Heavy metal concentration in soil and maize (Zea mays L.) in partially reclaimed refuse dumpsite 'borrow-pit'in Port Harcourt, Nigeria. Environmental technology and innovation, 18, 100745.

149. Sani, A. H., Amanabo, M., and Achimugu, M. D. (2023). Assessment of heavy metal pollution of drinking water sources and staple food cultivars around artisanal mining site in Igade-Mashegu, Niger State, Nigeria. World J. Biol. Pharm. Health Sci, 14, 306-319.

150. Sarwar, N., Imran, M., Shaheen, M. R., Ishaque, W., Kamran, M. A., Matloob, A., ... and Hussain, S. (2017). Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosphere, 171, 710-721.

151. Schwartz, F. W., Lee, S., and Darrah, T. H. (2021). A review of the scope of artisanal and small-scale mining worldwide, poverty, and the associated health impacts. GeoHealth, 5(1), e2020GH000325.

152. Schwitzguébel, J. P. (2017). Phytoremediation of soils contaminated by organic compounds: hype, hope and facts. Journal of Soils and Sediments, 17, 1492-1502.

153. Shah, V., and Daverey, A. (2020). Phytoremediation: A multidisciplinary approach to clean up heavy metal contaminated soil. Environmental Technology and Innovation, 18, 100774.

154. Shen, X., Dai, M., Yang, J., Sun, L., Tan, X., Peng, C., ... and Naz, I. (2022). A critical review on the phytoremediation of heavy metals from environment: Performance and challenges. Chemosphere, 291, 132979.

155. Shehu, A. H., Gumi, A. M., and Ismail, N. (2023). Phytoremediation of Heavy Metals: Reaction Mechanisms and Selected Efficient Technologies of Heavy Metal Contamination. In Heavy Metal Toxicity: Environmental Concerns, Remediation and Opportunities (pp. 245-269). Singapore: Springer Nature Singapore.

156. Shuaibu, L., Abdullahi, U., Yaradua, A. I., and Bungudu, J. I. (2021). Phytoremediation Potentials of Cynodon dactylon on Heavy Metal Contaminated Soils from Challawa Industrial Estate, Kano-Nigeria. Asian J. Appl. Chem. Res, 9, 25-36.

157. Silambarasan, S., Logeswari, P., Vangnai, A. S., Pérez, R., Kamaraj, B., and Cornejo, P. (2023). Co-application of citric acid and Nocardiopsis sp. strain RA07 enhances phytoremediation potentiality of Sorghum bicolor L. Environmental Science and Pollution Research, 30(36), 86244-86254.

158. Singh, N., and Balomajumder, C. (2021). Phytoremediation potential of water hyacinth (Eichhornia crassipes) for phenol and cyanide elimination from synthetic/simulated wastewater. Applied Water Science, 11(8), 144

159. Singh, S., and Fulzele, D. P. (2021). Phytoextraction of arsenic using a weed plant Calotropis procera from contaminated water and soil: growth and biochemical response. International Journal of Phytoremediation, 23(12), 1310-1318.

160. Singh, S., Kaushik, A., Bendi, A., Chetal, A., Ramakrishna, D. S., and Praveen, P. L. (2025). Constructed wetlands as bioeconomic solutions: rhizofiltration with macrophytes for heavy metal removal. Emergent Materials, 8(1), 75-83.

161. Singh, G., Pankaj, U., Chand, S., and Verma, R. K. (2019). Arbuscular mycorrhizal fungi-assisted phytoextraction of toxic metals by Zea mays L. from tannery sludge. Soil and Sediment Contamination: An International Journal, 28(8), 729-746.

162. Singh, T., and Singh, D. K. (2017). Phytoremediation of organochlorine pesticides: Concept, method, and recent developments. International journal of phytoremediation, 19(9), 834- 843.

163. Sivarajah, B., Campbell, L. M., Smol, J. P., Vermaire, J. C., and Kurek, J. (2024). Historical gold mining increased metal (loid) concentrations in lake sediments from Nova Scotia, Canada. FACETS, 9, 1-14.

164. Sivakumar, P., Kanagappan, M., and Das, S. S. M. (2016). Phytoremediation of tannery waste polluted soil using Hyptis suaveolens (Lamiaceae). Int J Pure Appl Biosci, 4(1), 265-272.

165. Song, X., Li, C., and Chen, W. (2022). Phytoremediation potential of Bermuda grass (Cynodon dactylon (L.) pers.) in soils co-contaminated with polycyclic aromatic hydrocarbons and cadmium. Ecotoxicology and Environmental Safety, 234, 113389.

166. Song, Q., and Li, J. (2014). Environmental effects of heavy metals derived from the e-waste recycling activities in China: a systematic review. Waste management, 34(12), 2587- 2594.

167. Stewart, A. G. (2020). Mining is bad for health: a voyage of discovery. Environmental geochemistry and health, 42(4), 1153-1165.

168. Susarla, S., Medina, V. F., and McCutcheon, S. C. (2002). Phytoremediation: an ecological solution to organic chemical contamination. Ecological engineering, 18(5), 647-658.

169. Taiwo, A. M., and Awomeso, J. A. (2017). Assessment of trace metal concentration and health risk of artisanal gold mining activities in Ijeshaland, Osun State Nigeria—Part 1. Journal of Geochemical Exploration, 177, 1-10.

170. Tabinda, A. B., Irfan, R., Yasar, A., Iqbal, A., and Mahmood, A. (2020). Phytoremediation potential of Pistia stratiotes and Eichhornia crassipes to remove chromium and copper. Environmental technology.

171. Tiemoko, T. P., Ouattara, G., and Ahoussi, K. E. (2024). Predictive Study of Trace Metal Pollution of Gold Panning Sites in Birimian Formations: Case of the Yaouré Furrow (Côte d'Ivoire). Open Journal of Applied Sciences, 14(7), 1691-1714.
172. Ting, W. H. T., Tan, I. A. W., Salleh, S. F., and Wahab, N. A. (2018). Application of water hyacinth (Eichhornia crassipes) for phytoremediation of ammoniacal nitrogen: A review. Journal of water process engineering, 22, 239-249.
173. Tiwari, J., Kumar, A., and Kumar, N. (2017). Phytoremediation potential of industrially important and biofuel plants: Azadirachta indica and Acacia nilotica. Phytoremediation potential of bioenergy plants, 211-254.
174. Trapp, S., and Karlson, U. (2001). Aspects of phytoremediation of organic pollutants. Journal of Soils and Sediments, 1, 37-43.
175. Ugochukwu, U. C., Chukwuone, N., Jidere, C., Ezeudu, B., Ikpo, C., and Ozor, J. (2022). Heavy metal contamination of soil, sediment and water due to galena mining in Ebonyi State Nigeria: Economic costs of pollution based on exposure health risks. Journal of Environmental Management, 321, 115864.
176. Umeoguaju, F. U., Akaninwor, J. O., Essien, E. B., and Amadi, B. A. (2022). Heavy metal profile of surface and ground water samples from the Niger Delta region of Nigeria: a systematic review and meta-analysis. Environmental Monitoring and Assessment, 194, 1-37
177. Umeoguaju, F. U., Akaninwor, J. O., Essien, E. B., Amadi, B. A., Igboekwe, C. O., Ononamadu, C. J., and Ikimi, C. G. (2023). Heavy metals contamination of seafood from the crude oil-impacted Niger Delta Region of Nigeria: A systematic review and meta-analysis. Toxicology Reports, 11, 58-82.
178. Upadhyay, V., Kumari, A., and Kumar, S. (2024). From soil to health hazards: Heavy metals contamination in northern India and health risk assessment. Chemosphere, 354, 141697.
179. Usman, K., Al Jabri, H., Abu-Dieyeh, M. H., and Alsafran, M. H. (2020). Comparative assessment of toxic metals bioaccumulation and the mechanisms of chromium (Cr) tolerance and uptake in Calotropis procera. Frontiers in plant science, 11, 883.
180. van Der Ent, A., and Rylott, E. L. (2024). Inventing hyperaccumulator plants: improving practice in phytoextraction research and terminology. International journal of phytoremediation, 26(9), 1379-1382.
181. Vishnupradeep, R., Bruno, L. B., Taj, Z., Karthik, C., Challabathula, D., Kumar, A., ... and Rajkumar, M. (2022). Plant growth promoting bacteria improve growth and phytostabilization potential of Zea mays under chromium and drought stress by altering photosynthetic and antioxidant responses. Environmental Technology and Innovation, 25, 102154.
182. Wang, H., Liu, H., Su, R., and Chen, Y. (2024). Phytostabilization of Heavy Metals and Fungal Community Response in Manganese Slag under the Mediation of Soil Amendments and Plants. Toxics, 12(5), 333.
183. Wang, P., Hu, Y., and Cheng, H. (2019). Municipal solid waste (MSW) incineration fly ash as an important source of heavy metal pollution in China. Environmental pollution, 252, 461- 475.
184. Wei, Z., Van Le, Q., Peng, W., Yang, Y., Yang, H., Gu, H., ... and Sonne, C. (2021). A review on phytoremediation of contaminants in air, water and soil. Journal of hazardous materials, 403, 123658.
185. Wijekoon, W., Priyashantha, H., Gajanayake, P., Manage, P., Liyanage, C., Jayarathna, S., and Kumarasinghe, U. (2025). Review and Prospects of Phytoremediation: Harnessing Biofuel-Producing Plants for Environmental Remediation. Sustainability, 17(3), 822.
186. Wiszniewska, A., Hanus-Fajerska, E., Muszyńska, E., and Ciarkowska, K. (2016). Natural organic amendments for improved phytoremediation of polluted soils: a review of recent progress. Pedosphere, 26(1), 1-12.
187. Wongsasuluk, P., Tun, A. Z., Chotpantarat, S., and Siriwong, W. (2021). Related health risk assessment of exposure to arsenic and some

heavy metals in gold mines in Banmauk Township, Myanmar. Scientific Reports, 11(1), 22843.

188. Wu, G., Wang, L., Yang, R., Hou, W., Zhang, S., Guo, X., and Zhao, W. (2022). Pollution characteristics and risk assessment of heavy metals in the soil of a construction waste landfill site. Ecological Informatics, 70, 101700.

189. Xiang, L., Harindintwali, J. D., Wang, F., Redmile-Gordon, M., Chang, S. X., Fu, Y., ... and Xing, B. (2022). Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. Environmental Science and Technology, 56(23), 16546-16566.

190. Xing, Y., Tan, S., Liu, S., Xu, S., Wan, W., Huang, Q., and Chen, W. (2022). Effective immobilization of heavy metals via reactive barrier by rhizosphere bacteria and their biofilms. Environmental Research, 207, 112080.

191. Xiyuan, X., Tongbin, C., Zhizhuang, A. N., Mei, L. E. I., Xiaoyong, L. I. A. O., and Yingru, L. I. U. (2008). Potential of Pteris vittata L. for phytoremediation of sites co-contaminated with cadmium and arsenic: The tolerance and accumulation. Journal of Environmental Sciences, 20(1), 62-67.

192. Yahaya, S. M., Abubakar, F., and Abdu, N. (2021). Ecological risk assessment of heavy metal- contaminated soils of selected villages in Zamfara State, Nigeria. SN Applied Sciences, 3(2), 168.

193. Yashim, Z. I., Kehinde Israel, O., and Hannatu, M. (2014). A Study of the Uptake of Heavy Metals by Plants near Metal-Scrap Dumpsite in Zaria, Nigeria. Journal of Applied chemistry, 2014(1), 394650.

194. Youssef, N. A. (2021). Changes in the morphological traits and the essential oil content of sweet basil (Ocimum basilicum L.) as induced by cadmium and lead treatments. International Journal of Phytoremediation, 23(3), 291-299.

195. Zacchaeus, O. O., Adeyemi, M. B., Adedeji, A. A., Adegoke, K. A., Anumah, A. O., Taiwo, A. M., and Ganiyu, S. A. (2020). Effects of industrialization on groundwater quality in Shagamu and Ota industrial areas of Ogun state, Nigeria. Heliyon, 6(7).

196. Zeng, P., Guo, Z., Xiao, X., Peng, C., Feng, W., Xin, L., and Xu, Z. (2019). Phytoextraction potential of Pteris vittata L. co-planted with woody species for As, Cd, Pb and Zn in contaminated soil. Science of the total Environment, 650, 594-603.

197. Zerizghi, T., Guo, Q., Tian, L., Wei, R., and Zhao, C. (2022). An integrated approach to quantify ecological and human health risks of soil heavy metal contamination around coal mining area. Science of the Total Environment, 814, 152653.

198. Zhang, X., Zhang, Y., Zhu, D., Lin, Z., Sun, N., Su, C., ... and Zheng, J. (2023). Chromium phytoextraction and physiological responses of the hyperaccumulator Leersia hexandra Swartz to plant growth-promoting rhizobacterium inoculation. Frontiers of Environmental Science and Engineering, 17(1), 9.

199. Zheng, S., Wang, Q., Yuan, Y., and Sun, W. (2020). Human health risk assessment of heavy metals in soil and food crops in the Pearl River Delta urban agglomeration of China. Food chemistry, 316, 126213.

200. Zhou, J. W., Li, Z., Liu, M. S., Yu, H. M., Wu, L. H., Huang, F., ... and Christie, P. (2020). Cadmium isotopic fractionation in the soil–plant system during repeated phytoextraction with a cadmium hyperaccumulating plant species. Environmental Science and Technology, 54(21), 13598-13609.