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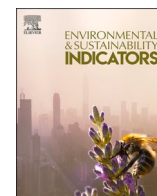


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Potentials of microbe-plant assisted bioremediation in reclaiming heavy metal polluted soil environments for sustainable agriculture

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ABSTRACT

As human population growth drives the demand for food, crop intensification has increased. However, urbanization, industrialization, and contamination of soil by heavy metals (HM) have become significant challenges to agricultural production. Urbanization activities jeopardize and/or harm soil health, which is critical for the environment, ecosystems, sustainable agriculture, and the global economy. Smelting, mining, and other industrial activities that release toxic HMs into the environment significantly reduce soil health, with serious consequences for both plants and humans. Furthermore, the presence of HM in the soil severely hinders sustainable agriculture. Therefore, to counteract the subsequent decrease in crop yield due to HM contamination, we must involve plants and appropriate microbes in eliminating these pollutants. This will lead to a more productive agriculture, food safety, and food security realization. Therefore, this study explored the efficacy, advantages, and limitations of current conventional methods of soil HM remediation as well as the potential of plants and microbes like *Pseudomonas aeruginosa*, *Vibrio parahaemolyticus*, *Alyxia rubricaulis*, and *Maytenus bureaviana* in the reclamation of HM polluted soil for sustainable agriculture. Employing natural and non-hazardous methods to remove these contaminants, as highlighted in this review, would help to improve soil health and quality, increase crop production, and promote sustainable agriculture, as outlined in the United Nations' Sustainable Development Goals.

1. Introduction

Pollution caused by heavy metals (HMs) - (metal elements with high atomic density) has been of great concern over the years, due to the continuous risks they pose to soil microbiota which further hampers agricultural and livestock production (Singh et al., 2022). Owing to their persistent nature, they accumulate in plants and soils, thus interfering with the physiological activities of plants like the exchange of gases, photosynthesis, and nutrient absorption, thereby disrupting agricultural production (Zaynab et al., 2022). Another major challenge posed by these environmental pollutants is their infiltration from the soil into crops and foods, the consumption of which results in debilitating health challenges and illnesses in humans and animals ranging from acute to chronic (Sharma and Agrawal 2005; Singh et al., 2022).

Apart from their natural occurrence, smelting and mining are examples of anthropogenic activities through which HMs are released into the environment, thus causing contamination (Cenova et al., 2022; Mishra et al., 2023; Madhav et al., 2024). During the process of smelting, mining, mineral processing, and metallurgical extraction, the tailings

produced which contain large quantities of HMs, constitute health hazards (de Souza Neto et al., 2020). To meet the economic demands of nations, there is a continuous increase in these anthropogenic activities, thus an increase in the presence of HMs in the environment (Kinuthia et al., 2020). While some of these, such as iron, are non-toxic and essential elements for human well-being (Raza'i et al., 2021), the long-term effect of the intake and accumulation of the harmful types would not only be detrimental to the soil microbiome but result in more complications in the long run (Yang et al., 2022; Madhav et al., 2024).

Heavy metals can be considered potentially toxic elements (Ahmad et al., 2021; Ghani et al., 2022a) and can be released as a result of anthropogenic and industrial activities, domestic emissions, waste discharge, or fuel and oil combustion. Infiltration into the skin, inhalation, and ingestion are all potential routes of exposure to these toxic substances. Even in trace amounts, these toxic elements are harmful to health and may cause a variety of illnesses such as respiratory disease, memory impairment, and cancer (Bhatti et al., 2022; Ghani et al., 2023; Soltani et al., 2023). In addition to polluting the environment, HMs may degrade the natural habitat and alter the soil microbiome.

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Cadmium (Cd), Lead (Pb), Mercury (Hg), Boron (B), and Chromium (Cr) are examples of HMs that have been reported to be present in the soil and sometimes in quantities that are large enough to harm the soil environment and threaten crop production (Zaynab et al., 2022). Their ability to interfere with the activity of beneficial soil microbes, which aid the growth and yield of plants/crops, causes a decrease in expected agricultural output (Pham et al., 2022). With the predicted increase in the world population by 2030, there is a need to invest greatly in sustainable agriculture and food production/supply (Wennersten and Qie 2018). To achieve this, all factors that might inhibit agricultural productivity, including soil HMs, must be conquered, while strategies for reclamation of HM-polluted agricultural soil must be enhanced.

Several studies have been carried out on the perilous effects of HMs on the environment, as well as the control measures to mitigate the menace caused by them, however, the impact of HMs on sustainable agriculture and crop production cannot be overemphasized and more studies are needed to provide effective strategies in combating the effects. This study hypothesizes that using microbes and plants as bioremediation strategies would greatly aid in the reclamation of heavy metal-polluted soils for sustainable agriculture. The study identified and reviewed the effects of HM pollution on agricultural soil, crop/livestock production, and the impact of toxic HM on agriculture, human health, food production, and sustainability. In addition, effective remediation techniques for HM-contaminated soils were reviewed.

2. Materials and methods

A literature search was conducted between November 2021 and June 2023. Data on HMs, their impact on soil biodiversity and sustainable agriculture, as well as bioremediation strategies, were retrieved from various online databases such as PubMed, Scopus, JSTOR, Science Direct, and Google Scholar. Additionally, books, theses, and dissertations were recovered from the North-West University (NWU) library, South Africa. Furthermore, terminologies and keywords such as HMs, sustainable agriculture, reclamation, bioremediation, electrokinetics, and environmental pollution were used for the search. We also saved the bibliographies from the recovered articles in the Endnote reference manager. Moreso, from each of the retrieved articles, information on toxic HMs and their examples, bioremediation, hyperaccumulators, and remediation strategies were obtained, while the scientific names of plants (hyperaccumulators) were validated.

2.1. Literature search results

A systematic approach called the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), as described by Page et al. (2021), was adopted for the selection of articles. We obtained a total of 548 relevant articles from various scientific databases. After the removal of duplicate articles, 490 were retained, out of which 10 were theses, dissertations, and books retrieved from the NWU library. Following the screening of titles and abstracts, 108 articles were excluded, leaving 382. The full text of the retained articles was reviewed in detail thus leading to the exclusion of 254 articles. Finally, 136 studies were considered appropriate and utilized for this review, constituting about 25% of the retrieved articles.

3. Prevalence of heavy metals (HMs) in the environment

In 2019, over 8000 cases of single exposure to HMs were reported by the American Association of Poison Control Centres (AAPCC), out of which about 2500 were in children younger than 6 years, while more than 3500 cases were reported in teenagers aged 19 years and older (Gummin et al., 2020). However, in water bodies such as rivers, lakes, and streams, studies have revealed the presence and high concentration of HMs (Woitke et al., 2003; Mekonnen et al., 2014). In Ethiopia, Dirbaba et al. (2018), among others, reported a high concentration of some

HMs, such as cadmium, on the surface sediments of rivers and streams. Likewise, toxic HMs like chromium and lead have been reported in waters, sediments, and soil in Ghana and other countries (Khelifi et al., 2022; Zakaria et al., 2022).

While HMs are major soil contaminants, they also abound in the air. For example, cadmium, lead and mercury are air pollutants being constantly released into the air by pharmaceutical, geogenic, agricultural, and industrial activities (Kumar et al., 2021). Commonly found in the air is cobalt, which has been reported in polluted air such as those containing dust (Hengstler et al., 2003). Huang et al. (2022) and Wang et al. (2020), reported the presence of cobalt, lead, arsenic, copper, mercury, zinc and cadmium in environmental dust in China. Similarly, Gangwar et al. (2019) found Lead, copper, zinc, Nickel and chromium to be major air pollution from waste recycling activities. In the same vein, food and beverages (alcoholic and non-alcoholic) produced locally are not exempt from the effects of environmental pollution caused by HMs. The study of Izah et al. (2016), is one of those that revealed the presence of HMs in alcoholic and non-alcoholic beverages produced locally, imported, and consumed in certain parts of Africa. These metals are categorized into classes that comprise of the highly toxic elements, macro-nutrients, micro-nutrients, precious elements, and radionuclides (Selvi et al., 2019), (Table 1).

3.1. Toxic heavy metals in the soil and their adverse impact on agriculture and health

Due to proximity, soil closer to industrial areas is at higher risk of pollution from dangerous HMs. When exposed to these hazardous elements, soil microbes react to changes in their environment, thereby causing alteration in the physical and chemical properties of the soil and consequently affecting the composition and functional capabilities of the soil microbial communities (Wang et al., 2007). Thus, the soil quality, structure, and plant growth processes carried out by these microorganisms are hampered (Setia et al., 2021). Furthermore, the soil microbial diversity and activities are not exempted from both the short-term and long-term adverse effects of HMs, these often manifest in the form of degradation and loss of vital nutrients (Zaynab et al., 2022). Examples of noxious HMs in the soil include:

3.1.1. Arsenic (as)

Is a ubiquitous element and notorious HM commonly referred to as “the king of poisons and poison of kings” (Aposhian et al., 2006). It is a naturally occurring chemical element that is widely distributed in the earth crust, readily bioavailable in groundwater and released into the environment in both inorganic (As^{3+} and As^{5+}) and organic forms through anthropogenic activities such as waste incineration, smelting, glassware production, and mining (Khan et al., 2021; Biswas and Ganesan 2024). Additionally, the occurrence of As in agricultural soil can inhibit photosynthesis and growth of plants, while in humans, it has been linked with metabolic abnormalities in mammalian cells, which leads to growth inhibition and cell death (Bernstam and Nriagu 2000; Khan et al., 2021). Furthermore, the bioavailability of this HM in water sources in its inorganic form is a major concern as it could infiltrate into crops and plants, subsequently getting into the food chain and being consumed by humans. Due to its carcinogenic and bioaccumulative

Table 1
Classes of heavy metals (HMs).

Classes	Examples
Highly toxic elements	Cadmium, Zinc, Mercury, Tin, silver, Platinum, Selenium, Lead, Arsenic
Macro-nutrients	Cobalt
Micro-elements	Copper, Iron, Manganese, Nickel, Chromium, Molybdenum
Precious elements	Gold, Silver, Platinum, Iridium, Osmium, Rhodium, Rhenium
Radio nuclides	Thorium, Strontium, Tritium, Cerium, Uranium, Radium, Praseodymium

nature, arsenic is one of the most harmful HMs on earth (Fashola et al., 2016; Biswas and Ganesan 2024).

3.1.2. Boron (B)

This is an important element for higher plants, however, in greater concentrations, it constitutes a menace to their growth and development due to its adverse effects on soil microorganisms (Schoderboeck et al., 2011). Boron toxicity occurs commonly in arid and semi-arid soils, through irrigation and other anthropogenic activities (Demetriou and Pashalidis 2012). In plants, the accumulation of B can inhibit functional, physiological and biochemical processes such as intake of water, carbohydrate metabolism, and carbon dioxide assimilation, which can further result in shoot necrosis as well as chlorosis (Vera et al., 2021). It has also been reported to impede plant and soil microbial relationships, thus inhibiting adequate growth/development and, in severe cases, leading to losses in agriculture (Vera et al., 2021). Yaman et al. (2024), observed from their study that, when the concentration of B increases in the soil, shoot and root lengths/weights are inhibited. In humans, B toxicity can lead to dermatitis, anorexia, hypothermia, and alopecia (Lim et al., 2022). Stürmer et al. (2024), examined the association of plasma boron levels with all-cause mortality and observed that higher levels of boron in the plasma were linked with a higher risk of all-cause mortality, especially in women.

3.1.3. Cadmium (Cd)

It is a non-essential and carcinogenic trace element predominant in the environment (water, air, and soil). Apart from anthropogenic activities such as smelting, metal production, and mining, synthetic fertilizers contribute to the concentration of Cd in the environment (Haider et al., 2021). The burning of fossil fuels such as coal also contributes to the release and presence of Cd in the air. It inhibits plant growth by infiltrating and accumulating in plants/crops (Haider et al., 2021). The presence of Cd in the environment alters the proper functioning of the ecosystem, as it is unsafe for most organisms, including the plant growth-promoting bacteria in the soil (Giaccon and Boon 2021). More so, an inverse relationship has been established between high concentrations of Cd and nutrient uptake, plant water relations, seedling germination, photosynthetic activity, enzymatic activities, chlorophyll level, carotenoid content, crop growth, development, and yield (Haider et al., 2021; Hussain et al., 2024). Through the food chain, Cd can be ingested by humans, resulting in organ damage, mitochondrial damage, an increased risk of osteoporosis, and various diseases such as diabetes, and cancer (Grioni et al., 2019; Zuhra et al., 2024).

3.1.4. Chromium (Cr)

It is an essential element and widely used in various industries, including mining, and the manufacture of certain chemicals. When disposed of in an unregulated manner, it finds its way into the environment (aquatic and terrestrial), thus entering the food chain and posing a severe threat to consumers (Jobby et al., 2018; Yang et al., 2020). Chromium occurs mainly in the form of ferrous chromite (FeCr_2O_4) and has been classified as a mutagen and Group A carcinogen. Due to its high oxidation power, it is capable of causing damage to the DNA of living organisms (Balali-Mood et al., 2021). Over time, it can accumulate in cells of the brain, heart, kidney, testes, and liver due to its low membrane permeability. It affects mitophagy and has been linked to DNA damage, anaemia, immunosuppression, phagocytic activity, and inflammation (Suljević et al., 2021; Alur et al., 2024). In plants, it is known to inhibit the germination of seeds, growth, nitrogen metabolism, chlorophyll synthesis, and photosynthesis, and also cause a reduction in soil biomass (USEPA 1998; Del Real et al., 2020; Qin et al., 2024). Aside from coal burning and drilling of oil wells, tanneries for metal plating can lead to the occurrence of Cr in the environment (Sharma et al., 2021).

3.1.5. Cobalt (Co)

Co can exist both as sulphide and oxide ores, and at a moderate or appropriate quantity, it is vital for plant health, growth, development, and metabolism of root nodules in leguminous plants (Zhu et al., 2021a). However, at higher concentrations in the soil, it exerts harmful effects on crops, which manifest in the form of plant discoloration, falling leaves, premature leaf closure, and reduced shoot weight (Mahey et al., 2020). According to Azarakhsh et al. (2015), Salam et al. (2024) and Shih et al. (2021), greater concentrations of Co may result in reduced uptake of nutrients, oxidative stress, the production of reactive oxygen, the formation of hydrogen peroxide, an increase in proline, and inhibition of antioxidant enzyme activities. In addition, nitrogen metabolism is affected while photosynthetic pigments are reduced by increased Co in the soil (Azarakhsh et al., 2015). In humans, the infiltration of this HM into food may result in cobalt poisoning, which has been linked with severe cardiomyopathy and hypoxia in cardiomyocytes (Giaccon and Boon 2021; Zhu et al., 2021a).

3.1.6. Copper (Cu)

Cu exists in both oxidized and reduced states (Cu (II) and Cu (I) respectively), and shares similar characteristics with cobalt, due to its ability to exist as sulphide and oxide ores (Xu et al., 2021). Although toxic at high concentrations, Cu is an essential micronutrient in moderate quantities as it aids the flow of electrons and catalyzes redox reactions (Sandoval-Pauker et al., 2021). Extreme concentrations of Cu in the soil have hazardous effects on soil microorganisms, resulting in changes in soil equilibrium, consequently affecting soil health, soil microflora, fauna, fertility, crop development, and production (Shaw et al., 2020; Tu et al., 2024). In humans, it is an essential trace element that is important for bone health and the proper functioning of the immune system. It has been established to possess growth-promoting importance, antibacterial, anti-parasitic, and antifungal characteristics (Li et al., 2021). However, in high concentration, it is known to inflict gastrointestinal problems such as diarrhoea and vomiting, it has also been linked with renal failure, mitochondrial dysfunction, endoplasmic reticulum stress, copper-mediated cell death, and intravascular haemolysis (Franchitto et al., 2008; Abdullah et al., 2024).

3.1.7. Lead (Pb)

Pb is a naturally non-degradable element that is harmful even at the lowest concentration (Trujillo-Vázquez et al., 2023). Being commonly found in soil and groundwater, lead penetrates bacteria cells, changes the protein and nucleic acid conformation, disrupts cellular function, inhibits enzyme activity, damages the DNA structure, and disturbs several physiological processes in plants (Bruins et al., 2000; Pourrut et al., 2011). Instability in the uptake of ion by plants is a major consequence of lead toxicity, and this inhibits plant growth (Jaishankar et al., 2014). According to Aslam et al. (2021) and Ilyas et al. (2024), lead toxicity inhibits guard cells significantly and impedes cell wall elasticity, seed germination, crop yield, leaf, and chlorophyll development. House paint, gasoline, plumbing pipes, and lead batteries, are sources of lead, hence, exposure to these might result in oxidative stress and lead poisoning in humans (Charkiewicz and Backstrand 2020; Carroll et al., 2021; Harshitha et al., 2024).

3.1.8. Mercury (Hg)

This is a major HM that penetrates and accumulates in the body through the food chain. Apart from gold mining, mercury pollution occurs from paper and pulp preservatives, activities of industries like pharmaceuticals, chlorine, and caustic soda, as well as careless waste disposal (Jaishankar et al., 2014). In plants, Hg toxicity does not only impede growth but also causes long-term damage to the soil microbiome, consequently altering soil fertility, and impairing the physiological and metabolic activities of plant (Maqsood et al., 2024). According to Gallego et al. (2002) and Malar et al. (2015), oxidative stress is induced in plants as a result of high concentrations of mercury

ions. This is done by increasing the formation of reactive oxygen species such as hydroxyl radical and hydrogen peroxide in plant cells, which creates a negative effect on fatty acids, chlorophyll contents, nucleic acids, and proteins (Malar et al., 2015). Through the aid of microbes, the mercury present in soil and water is converted to methylmercury, which is a more poisonous form of mercury and has been categorized as highly carcinogenic (USEPA 1998). Exposure to this form of mercury commonly used as a preservative for animal grains and its accumulation in the human body can cause adverse effects such as damage to kidney and brain tissue, impairment of the immune system, and other forms of ailment ranging from mild to severe (Guzzi et al., 2021; Zafar et al., 2024).

3.1.9. Nickel (Ni)

It is an HM used immensely in industries, hence its wide occurrence in the environment as a pollutant (Das et al., 2019). It's mostly found at low concentrations in the soil and the environment generally and bound with sulfur or oxygen, therefore forming sulphides or oxides in the earth's crust (Yang and Ma 2021). In plants, nickel affects metabolic activities, causing inhibition of growth, induction of necrosis, chlorosis, wilting, impairing pigment concentration, and damaging the leaf photosynthetic system (Bhalerao et al., 2015; Saqib et al., 2024). Some Ni compounds, such as nickel (II) nitrate-Ni(NO₃)₂ and nickel (II) chloride-NiCl₂ have been classified as human carcinogens by the International Agency for Research on Cancer (IARC) (IARC 1990), hence, the World Health Organization recommends a safe limits of 0.02 and 0.05 ppm Ni in wastewater and agricultural soils respectively (Boffetta 1993; Kinuthia et al., 2020). Human exposure to Ni (which is capable of harming the colon) occurs mainly through air, food, and water, although it can also get into the bloodstream through inhalation and skin infiltration (Genchi et al., 2020; Zheng et al., 2024) (see Fig. 1).

3.1.10. Zinc (Zn)

This is an essential heavy metal needed for physiological activities in the human body, it is vital for the repair of tissues in the human body as well as for proper growth and development. Although nontoxic at moderate concentrations, exposure to high concentrations of this heavy metal could result in intoxication, manifesting in the form of breathing difficulty, coughing, and nausea in humans. Being found generally in soil and water, an extreme concentration of zinc in these ecosystems can tamper with the diversity of microbes, thus affecting the absorption and bioavailability of other metals (Hussain et al., 2022). By affecting the soil microbial diversity, high concentrations of zinc may impact soil fertility, crop quality, yield plant growth, and crop production (Raza'i et al., 2021; Kaur et al., 2024). Reversing the alteration caused by HM in the soil can be demanding, likewise, the ravaging effects of their infiltration into the food chain can be overwhelming. Table 2 summarizes the sources of various HMs, their action mechanisms, and the adverse effects of these elements on sustainable agriculture, while Fig. 2 illustrates how air, water, and soil pollution by HMs contaminates the atmosphere, poses threats to life, and also affects plant growth and production by causing ecotoxicity in the soil microbiome as well as in aquatic habitats.

4. Strategies for heavy metal remediation and their challenges

Owing to the urgency of achieving sustainable agriculture, driven by the ever-increasing global population, the revamping and remediation of soil microbial communities is crucial. This will prevent the overwhelming occurrence of HM in the environment and the infiltration of lethal HM into the food chain. Examples of techniques being used with respect to this include, chlorination/thermal treatment, chemical extraction, and adsorption. However, these methods have not been without negative consequences.

4.1. Chlorination and thermal treatment

This chemical/technological approach has been recognized as an effective method for significantly reducing the Pb, Cu, Zn, and Cd levels in HM contaminated soil, consequently minimizing the threat posed by these HMs on the soil microbiome and plants (Nowak et al., 2012; Li et al., 2019; Xia et al., 2020). For this process, which is carried out in a cylindrical rotary kiln, CaCl₂ and MgCl₂ are the metal chlorides frequently utilized due to their high-chlorination efficiency. Based on the average target temperature of about 950 °C, this procedure favours the immobilization of HMs in the soil and yields remediated soil free from Pb and Cd while significantly reducing the concentrations of Cu and Zn (Nowak et al., 2012; Li et al., 2019; Xia et al., 2020). Despite the applicability of this method in HM remediation, some drawbacks have been recorded, which are highlighted below.

4.1.1. Limitations

Regardless of its suitability, this method may elicit potential long-term effects due to the by-products of chlorination, such as trihalomethanes, which have been identified as carcinogenic (Nagai et al., 2012). It can also lead to the accumulation of chlorine in the soil, thus resulting into excessive deposit of the micronutrient, which injures mature leaves and plant roots and alters the activity of beneficial soil microbes, especially bacteria (Gryndler et al., 2008; Sun et al., 2022). Also, when chlorine deposits in the soil are washed into waters or rivers, it can pose a major threat to aquatic organisms (Organization 1996).

4.2. Adsorption

This technique is commonly utilized for the removal of HMs such as Pb, Zn, Cu as well as metal ions, from several industrial effluents. It is considered suitable due to its cost, economic effectiveness, and ease of operation (Lakherwal 2014). Adsorbents such as activated carbon, kaolinite, polymeric materials, zeolites, lignin, and clay are employed for the removal of HM. Most of these adsorbents are easily and locally available in large quantities, however, there are several limitations to these techniques, which are highlighted below.

4.2.1. Limitations

Weak specificity and high cost of adsorbent are major drawbacks of this procedure. The adsorbents mentioned above suffer from low adsorption capacities and separation inconvenience. Therefore, efforts are still needed to exploit new, promising adsorbents.

4.3. Ion exchange

In addition to iron, zeolites, and activated carbon, ion-exchange resins show efficiency in HM remediation. The results from the study of Feng et al. (2010) showed that Duolite Gt-73 and Amberlite IRC-748-Rohm and Haas, have the capability to significantly reduce the concentration of cadmium, copper, and lead from 1000 µg/L to below 5 µg/L. The study of Budak (2013) and Sikora et al. (2021) confirms the potency of ion-exchange resin beads in the remediation of lead, nickel, cadmium, and mostly copper. Apart from its reduced cost, this procedure has been considered to possess high processing capacity.

4.3.1. Limitations

According to the study of Esmaeili and Foroutan (2015); Dosuna-Rodríguez and Gaigneaux (2012), low thermal stability, deactivation by cations (Na) and metals such as iron, and pollution of larger quantities of resins in the presence of organic materials are the challenges of this technique. Moreover, ion-exchange resins may not be effective in cases of high contamination.

Table 2
Effects of soil heavy metals (HMs).

Heavy metals	Sources	Action mechanism	Effects on agricultural soil, soil microbes and crop production	Effects on human health	EU standard in soils (µg/g)	Reference
Arsenic	Waste incineration, smelting, natural processes, mining, pesticides, glassware operations	Generates Reactive Oxygen Species (ROS) Damages the dynamic DNA maintenance system Inhibits formation of ATP Damages capillary endothelium Epigenetic alterations Generates ROS	Affect soil health, fertility, crop development and production,	Growth inhibition, cell death, cancer	20	(Rahaman et al., 2013; Engwa et al., 2019; Balali-Mood et al., 2021)
Boron	Naturally occurring, mining and other anthropogenic processes		Causes chlorosis and necrosis, Induces brown lesions at leaf sheaths, spikes and stems, Delayed emergence, reduction in the height of stem	Weight loss, respiratory distress, irritation	1	(Parks and Edwards 2005; Brdar-Jokanović 2020; Hadrup et al., 2021)
Cadmium	Industrial discharge and waste, incineration, fuel combustion, mining, and smelting	Apoptosis, altered phosphorylation cascades, unbalanced Ca, Zn and Fe homeostasis. Inhibition of cell division Damage of Nucleic acid	Inhibits root growth, affect germination of plant seeds and seedling growth, affects chloroplasts morphology, biosynthesis of chlorophyll and activity of enzymes, thus affecting photosynthesis	Kidney dysfunction, bone disease, disorders in the gastrointestinal tract, liver damage, High blood pressure	3	(Wang et al., 2018; Balali-Mood et al., 2021; Zhu et al., 2021b)
Chromium	Industrial coolants, metal plating, leather tanning	Damages the DNA Causes genomic instability	Suppresses biological activities of soil microbes, modifies soil environment, influence enzymatic activities in the soil by affecting the soil microorganisms.	Pulmonary sensitization, cancer, DNA damage, affects the immune system	150	(Wyszkowska 2002; Ray and Ray 2009; Balali-Mood et al., 2021)
Cobalt	Batteries, surgical implants, coloured glass, paints, Co-containing sludge, deposits from combustion, mining, refineries and phosphate fertilizers	Cause disturbance of mitotic processes	Affects soil basal respiration, arylsulphatase and acid phosphatase	Gastrointestinal problems, vision impairment, dermatitis, thyroid damage, Cardiomyopathy, rhinitis, asthma, and death	—	(Leyssens et al., 2017; Lozano et al., 2022)
Copper	Mining, Industrial wastes, mineral leaching, metal plating	Competitive inhibition Disruption of cell membrane	Higher concentration kg ⁻¹ affects soil functionality and the community structure of microbes in the soil	Apoptosis, damage to the DNA, reduced cell growth,	140	(De Lillo et al., 2018; Shaw et al., 2020; Sharma et al., 2021)
Lead	Fossil fuel burning, mining, cosmetics, and battery manufacturing industries	Induces cellular damage through the formation of ROS, Inhibits the actions of calcium/calcium dependent processes, alters the configuration of sulphhydryl and amide groups of enzymes, and reduces their ability	Causes soil microbial DNA damage, inhibits chlorophyll production, root elongation and development of seedlings	Respiratory and cardiovascular disorders, anaemia, brain, and kidney damage	300	(Tchounwou et al., 2012; Tóth et al., 2016; Zulfiqar et al., 2019)
Mercury	Pesticides, industrial/hospital waste incineration, mining, coal combustion, volcanic eruptions, emission from oceans, geologic deposits	Generation of free radicals that damages biomolecules by inducing oxidative stress. Production of reactive oxygen species Inhibition of Glutathione peroxidase Inhibition of vital enzymes	Affect soil microbial community structure, reduced nitrogen-fixation rate, inhibition of plant growth	Affects the liver and the central nervous system. Gastrointestinal ulceration, renal failures, redness of hands and feet, cardiovascular and hormonal problems	0.02	(Hyun et al., 2021; Seydi and Pourahmad 2023)
Nickel	Emission from industries (such as the battery industry), forest fires, volcanic eruptions, combustion of coal/diesel/fuel, certain food/cooking utensils	Regulation of transcription factors, controlled expression of certain genes and generation of free radicals which aids carcinogenic processes	Affects soil health, crop quality,	Impairment of cell membrane function, neuronal degeneration of the hypothalamus, significant decrease in the level of androgen and estrogen, oxidative stress and apoptosis	75	(Genchi et al., 2020; Yang and Ma 2021)
Zinc	Smelting, industrial wastes, electro-plating, plumbing.	Inhibition of enzyme activities Inhibition of cell division.	Inhibits growth and root elongation, reduces chlorophyll content in leaf, reduce root and shoot biomass.	Hepatic DNA damage, nausea, diarrhoea, vomiting, abdominal cramps and death.	300	(Yang et al., 2015; Wang et al., 2016; Charkiewicz and Backstrand 2020; Eldidamony et al., 2021; Elleuch et al., 2021).

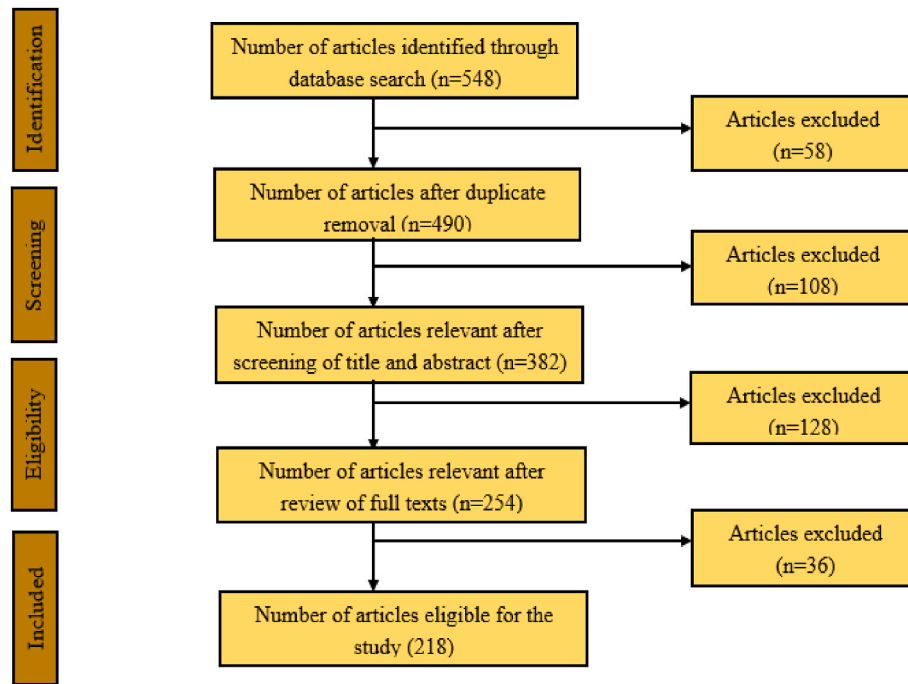


Fig. 1. Flow diagram for the inclusion and exclusion of articles.

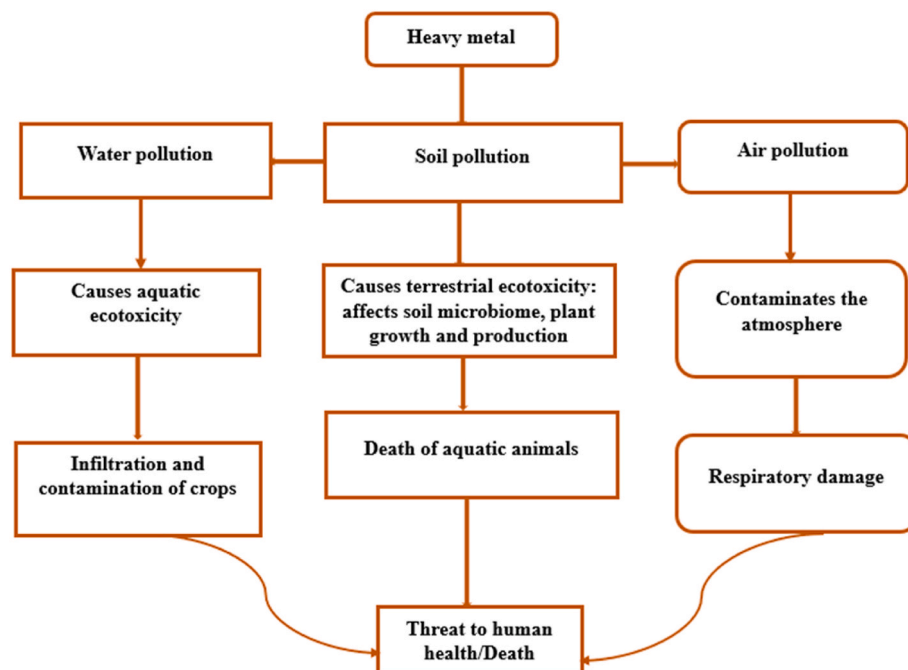


Fig. 2. A schematic illustration for the effects of HMs on the environment.

4.4. Electro-kinetics

This procedure is applied to remove HM contaminants from low permeable, contaminated soil by applying direct current. A direct current of low voltage is applied to electrodes in the soil, thus creating an electric field in the soil. Through the electric field created, HM is mobilized and then extracted from the soil (AEC 2000). With a removal rate of about 24–84 %, this method is significantly potent in dislodging HMs (Wang and Tam 2019). The ability to engage this procedure in removing contaminants from zones with low permeability (which is

difficult to carry out with some other existing methods) and the possibility of conducting this procedure within the remediation site (in-situ) is a main advantage (Brusseau 2019).

4.4.1. Limitations

Alteration of the soil's pH especially when current is induced for a longer period, is a major challenge of this technique. Also, it's been noted as a time-demanding process, and metals buried in the soil could change the voltage gradient, cause a decrease or diversion of current flow, or stop the flow altogether. While low-permeable soils can be

easily remediated with this method, soils with high permeability reduce the efficiency of electro-kinetics (Cauwenberghe 1987).

4.5. Chemical precipitation of heavy metals

Due to its simplicity and cheap cost, chemical precipitation is one of the most frequently used techniques for the removal of HMs. Through the use of hydroxides (calcium hydroxide or sodium hydroxide) or sulphides (such as sodium sulphide, calcium sulphide, hydrogen sulphide, the metals are transformed into insoluble form as a result of the chemical reaction between the precipitating reagent and the HM compounds (Dahman 2017; Pohl 2020).

4.5.1. Limitations

Extremely low solubility of metal sulphides and release of hazardous hydrogen sulphide (Pohl 2020).

4.6. Bioleaching

This process is aimed at recovering HMs especially from sludge by microorganisms such as *Thiobacillus*. Being a cost-effective and eco-friendly natural process, it doesn't cause a release of hazardous gases, which could result in secondary pollution (Nguyen 2003). Being eco-friendly and cheaper, this procedure has made up for the drawbacks of physicochemical remediation. It is a more sustainable technique for reclaiming soil environments polluted with HMs, thus making them more suitable for agricultural practices. The bioleaching process is facilitated by certain acidophilic bacteria, which have the ability to oxidize reduced sulfur or ferrous iron so as to produce acidity (Tichy 1998). The major types of bacteria optimized in this process are *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* (Marchiorretto et al., 2003).

4.6.1. Limitations

In contrast to other methods of HM remediation, the bioleaching process is a slow procedure that would also need follow-up treatment as the filter residue may retain some HMs that cannot be leached (Gao et al., 2021). Long-term exposure to toxic HMs can result in severe effects that could be life-threatening (e.g. cancer) due to the debilitating effects of these pollutants (Dhane et al., 2024). According to Witkowska et al. (2021), an excellent approach to limiting HM pollution is to control their concentration and influx into the environment. Identifying and understanding the sources and routes of pollutant exposure is a crucial step in reducing the risks posed by toxic HMs. Targeting the source of exposure with interventions to control HMs is crucial to identify, determine, examine, manage, and potentially eradicate the pollution source, particularly in industries. We should consider the acute and long-term effects of the pollutant on health.

It is important to monitor the populations exposed to HM pollution, both physically and biologically. Frequent monitoring and evaluation can assist in identifying risks or threats posed by HMs and guide them in taking the right remedial steps. While it may not be regarded as a major control measure, industrial or environmental exposure may be prevented by industrial hygiene or environmental control approaches. Moreover, adequate training and education of personnel in the industrial and research areas, as well as health professionals, policymakers, and the general public, about the risks and threats posed by toxic HM pollution and strategies for minimizing these risks, would be of great help in the prevention and control of exposure to HMs. Adequate education and awareness of the effects of toxic HMs by health policymakers would guide them in taking the precautions needed to take decisions on permitting further circulation of HMs into the environment (Lucchini et al., 2015). We further recommended implementing increased awareness and campaigns on the potential acute and chronic health effects of HMs.

5. Bioremediation

Being a more sustainable and less expensive technique, bioremediation has been a recommended method in the treatment of heavy metal-polluted soil (Pearce et al., 1995). This process degrades HM and causes it to change from one oxidation state to another, making it less poisonous, leachable, and bioavailable. Although plants are commonly used for this purpose (phytoremediation), utilization of suitable microbes has been proven to be a productive strategy for the reclamation of HM-polluted soil (Wang and Tam, 2019; Saha et al., 2021). Microbes, including bacteria, fungi, and algae such as *pseudomonas putida*, *chlorella vulgaris*, and arbuscular mycorrhizal fungi, are used for the immobilization, detoxification, and removal of various pollutants from the environment through biostimulation, bioaugmentation, and intrinsic bioremediation (Chekroun et al., 2014; Ayangbenro and Babalola, 2017; Tomer et al., 2021; Omotayo and Babalola, 2023). We introduce these microbes into the soil, providing them with a conducive environment and nutrients to multiply and thrive, thereby carrying out the remediation process.

In addition, this method optimizes the metabolizing potentials of certain microorganisms to modify contaminants such as HMs into non-toxic or less hazardous forms. The microorganisms degrade contaminants by utilizing them as an energy source (Ayangbenro and Babalola 2017). Bioremediation can be aerobic, involving microbial reactions that make use of oxygen. It can also be anaerobic, involving microbial reactions that occur without oxygen, and this involves processes like methanogenesis, fermentation, and reductive dichlorination (Elyamine et al., 2021).

5.1. Phytoremediation

This strategy is applicable when the HM pollutants are within the plant root zone and cover a larger area. It involves the use of plants in the removal/clean-up, transfer, stabilization, and destruction of HM in polluted soils. Being powered by solar energy, and due to plants' ability to absorb ion compounds from the soil, phytoremediation is a productive and environmentally friendly approach (Yan et al., 2020b). In their study, Jacob et al. (2018) and DalCorso et al. (2019), made it known that through the root systems of certain plants, they can establish a rhizosphere ecosystem to accumulate and modulate the bioavailability of HMs, thereby redeeming the polluted soil. To achieve phytoremediation, plants may be engaged to either reduce the bioavailability of HM in the soil or extract HM from the soil through a process called phytoextraction. There are several soil phytoremediation mechanisms.

- Rhizodegradation and phytodegradation

Rhizodegradation, also regarded as phytostimulation, involves the release of nutrients through the root exudates into the rhizosphere, thereby supplying the microbes in this region with vital nutrients to carry out the degradation process (Dowling and Doty 2009). The rhizosphere microbiome, which receives sugars, amino acids, and other nutrients through root exudate discharge as well as phytohormones, assists in the degradation of toxic HMs. In phytodegradation, plants can directly absorb and break down contaminants into less toxic compounds and distribute them within plant tissue; that is, it entails the degeneration of HM through metabolic activities that occur in plant tissues (Greipsson 2011; Omotayo et al., 2021; Omotayo 2022).

- Phytofiltration

This entails the absorption and adsorption of toxic HMs by plant roots (rhizofiltration), shoots (caulofiltration), and seedlings (blastofiltration). The pollutants are removed from the contaminated soil through precipitation, absorption, and accumulation into plant biomass (Mahajan and Kaushal 2018). Plant roots are used to absorb/concentrate and

precipitate toxic HMs following the acclimatization of the hyper-accumulators to contaminated environments (Yan et al., 2020a). These hyperaccumulators are then transferred to contaminated soil and harvested when their roots are saturated with the contaminants.

- Phytostabilization

This entails the release of chemical compounds by plants into the soil which causes the immobilization of HM leading to a change in their redox state and consequently a decrease in their bioavailability (Li-qun et al., 2009). This technique is targeted towards minimizing the mobility of these toxic compounds by establishing plant cover on toxic HM-contaminated sites (Kafle et al., 2022). The contaminants are taken up and sequestered in the root system (in the root cell vacuole through cellular processes), precipitated, and immobilized by root exudates (Kafle et al., 2022). Plant roots limit the mobility and bioavailability of the pollutants through their stabilizing ability, thus reducing the toxic effects of the HMs.

- Phyto-accumulation/phytoextraction

This process involves the absorption of toxic HMs by plant roots (hyperaccumulators) and their transfer to the shoots followed by its deposit at the aboveground part of plant tissues (leaves and shoots), which are not active metabolically (Greipsson 2011). Through chelation with metals and their metabolites, hyperaccumulators absorb toxic HMs from the soil, thus reducing HM toxicity (Yaqoob et al., 2019; Kafle et al., 2022; Khan et al., 2023).

- Phytovolatilization

HMs are taken up by plant roots, modified and converted into gases, and released into the atmosphere (Khan et al., 2023). This occurs when plants take up water and contaminants like HMs. The water and contaminants that move from the roots to the leaves change and get modified as they travel to the leaves and finally evaporate into the atmosphere (Kafle et al., 2022; Khan et al., 2023).

5.1.1. Plants capable of phytoremediation

There are about 500 plant species known as hyperaccumulators, capable of storing up and tolerating high levels of HMs in their roots and shoots (Muszynska and Hanus-Fajerska 2015). In the phytoremediation process, hyperaccumulators absorb the toxic metals from soils at high concentrations. Table 3 shows examples of these valuable plants and the metals they commonly absorb.

5.1.2. Potentials of phytoremediation

The use of natural resources in the prevention and control of pollutants and toxins has been highly recommended and noted to be effective, mostly without any significant hazardous consequences. The ability of hyperaccumulators to absorb and tolerate high levels of HMs makes them suitable for the reclamation of contaminated soil. Plants such as those listed above (Table 3) can return the soil to a less toxic state suitable for sustainable agriculture. However, to achieve optimal success with phytoremediation, proper plant selection needs to be done, as most of the identified hyperaccumulators grow slowly and have small sizes (Comis 1996). The ability of some hyperaccumulators, such as *Alyssum murale*, to tolerate extreme environmental and climatic conditions, like drought, makes them stable and capable of accumulating HM pollutants. Therefore, intercropping with hyperaccumulator plants such as this would significantly enhance the uptake of heavy metal from the soil environment, thus reducing the risk of contamination of the cultivated plants drastically (Hu et al., 2019). Crop rotation techniques involving hyperaccumulators are also viable means of getting rid of HMs. In their study, Saad et al. (2018) found that rotating legumes with *Alyssum murale*, helped in the reduction of Nickel from the soil and a high

Table 3

Plants with phytoaccumulation capability.

Plant species	Heavy metal	References
<i>Aeolanthus biformifolius</i> , <i>Cicer arietinum</i> , <i>Eleocharis acicularis</i> , <i>Ipomoea alpine</i> , <i>Pteris biaurita</i> , <i>Pteris cretica</i> , <i>Pteris longifolia</i> , <i>Pteris Umbrosa</i> , <i>Pteris vittata</i> , <i>Pityrogramma calomelanos</i> , <i>Pteris multifidi</i> , <i>Pteris quadriaurita</i> , <i>Pteris rhyukyuensis</i>	Arsenic, Chromium, Copper	(Koller et al., 2008; Dasgupta et al., 2011; Yang and He 2016; Nurfitri et al., 2017)
<i>Azolla pinnata</i> , <i>Arabidopsis halleri</i> , <i>Betula occidentalis</i> , <i>Brassica nigra</i> , <i>Brassica juncea</i> , <i>Betula occidentalis</i> , <i>Cicer arietinum</i> , <i>Deschampsia cespitosa</i> , <i>Eleocharis acicularis</i> , <i>Euphorbia cheiradenia</i> , <i>Helianthus annuus</i> , <i>Medicago sativa</i> , <i>Noccaea rotundifolia</i> , <i>Phytolacca americana</i> , <i>Sedum alfredi</i> , <i>Salsola kali</i> , <i>Thlaspi rotundifolium</i> , <i>Thlaspi calaminare</i> , <i>Thlaspi caerulescens</i> , <i>Turnip landraces</i>	Cadmium, Lead, Zinc	(Reeves et al., 2018; Jahromi et al., 2019; McBride and Zhou 2019; Kumar et al., 2020; Muro-González et al., 2020; Rezaeian et al., 2020; Cenova et al., 2022)
<i>Haumaniastrum robertii</i> , <i>Haumaniastrum katangense</i> , <i>Haumaniastrum robertii</i> , <i>Haumaniastrum villosum</i>	Cobalt	(Kabeya et al., 2018; van der Ent et al., 2019)
<i>Astragalus racemosus</i> , <i>Astragalus bisulcatus</i> , <i>Astragalus convallarius</i> , <i>Lecythis ollaria</i> , <i>Alyssum caricum</i> , <i>Alyssum bertolonii</i> , <i>Alyssum corsicum</i> , <i>Alyssum markgrafii</i> , <i>Alyssum murale</i> , <i>Alyssum serpyllifolium</i> , <i>Alyssum pterocarpum</i> , <i>Alyssum heldreichii</i> , <i>Alyxia rubricaulis</i> , <i>Berkheya coddii</i> , <i>Isatis pinnatifolia</i> , <i>Maytenus bureaviana</i> , <i>Macadamia neurophylla</i> , <i>Phyllanthus serpentinus</i> , <i>Psychotria douarrei</i>	Selenium	(Alford et al., 2012; Lindblom et al., 2013; Statwick et al., 2016)
<i>Achillea millefolium</i> , <i>Armoracia lapathifolia</i> , <i>Cicer arietinum</i> , <i>Festuca rubra</i> , <i>Helianthus tuberosus</i> , <i>Juncus maritimus</i> , <i>Marrubium vulgare</i> , <i>Poa pratensis</i> , <i>Rumex induratus</i> , <i>Silene vulgaris</i>	Nickel, Manganese	(Brooks et al., 2001; Broadhurst and Chaney 2016; Bani et al., 2018; Nkrumah et al., 2018; Dao et al., 2020)
	Mercury	(Moreno-Jiménez et al., 2007; Antonkiewicz et al., 2018; Pacwa-Płociniczak et al., 2018).

concentration of this HM was found in the root and leaves of the hyperaccumulator plant. Similarly, Yang et al. (2011) found that rotating *Noccaea caerulescens* with *Brassica rapa* L. spp. *Chinensis* cv (pakchoi) helped in a significant reduction of Cd from the soil and shoot of pakchoi.

5.2. Microbe assisted bioremediation

Engaging suitable microorganisms in redeeming HM-polluted soil has been proven to be efficient and less expensive. The process of remediation by microbes can either be 'in-situ' or 'ex-situ' as illustrated in Fig. 3 (Lombi and Hamon 2005). Both methods engage microorganisms, and with the aid of enzymes such as oxidoreductases and dioxygenases, toxic HMs are converted into less harmful forms in a process called bioattenuation (Saha et al., 2021). Other approaches involves biostimulation and bioaugmentation (Saha et al., 2021). In the process

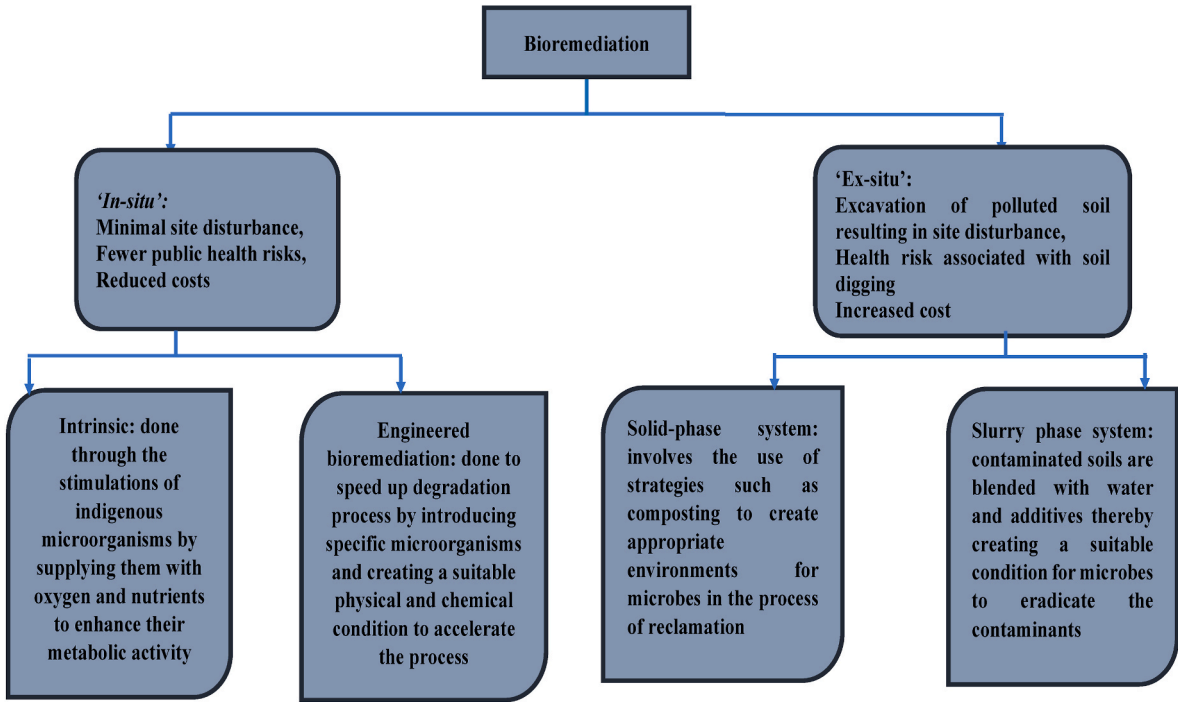


Fig. 3. In-situ and Ex-situ bioremediation processes.

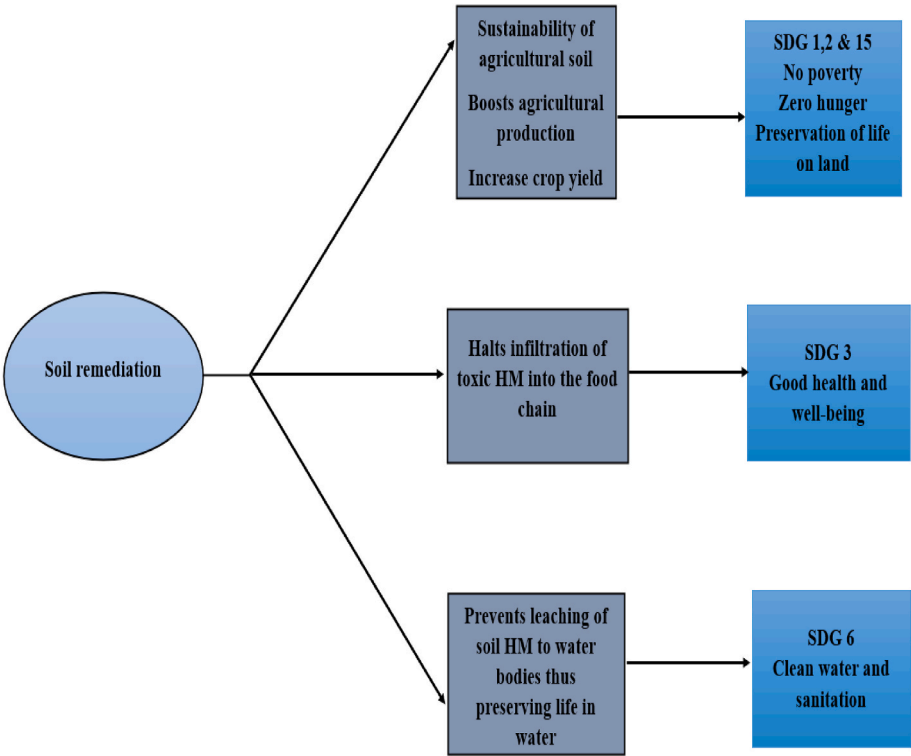


Fig. 4. Soil bioremediation, reclaim of polluted soil for agriculture, and the SDG's.

of microbial remediation, microorganisms such as *Pseudomonas*, *Rhodococcus*, and other aerobic bacteria utilize the HM contaminants to obtain carbon and energy while cleaning up the ecosystem (Table 4) - (Liu et al., 2020) (see Fig. 4). Moreover, anaerobic bacteria, such as those belonging to the *Dehalobacter*, *Desulfuromonas*, and *Dehalococcoides*, degrade Heavy metal compounds (Omotayo et al., 2021). The methylotrophs such as

Methylocapsa, *Methylovirgula*, and *Methylosinus* helps utilize methanol produced during carbon cycling and by the decomposition of plants pectin and lignin (Mathé et al., 2019). Fungi are not exempt from remediation activities, through biosorption process, *Aspergillus*, *Saccharomyces*, *Rhizopus* reduce heavy metal contamination. Mycorrhizal fungi associated with plant roots also help in the reduction of soil HM through the accumulation of these pollutants in their hyphae or

Table 4
Microorganisms capable of bioremediation.

Microbial species	Heavy metal	Reference
<i>Arthrobacter viscosus</i> , <i>Aeribacillus pallidus</i> , <i>Bacillus badius</i>	Lead (Pb)	(Rebello et al., 2021; Pham et al., 2022)
<i>Bacillus badius</i> AK, <i>Klebsiella pneumoniae</i> , <i>Pseudomonas putida</i> , <i>Pseudomonas aeruginosa</i> , <i>Saccharomyces cerevisiae</i>	Cadmium (Gunsalus et al.)	(Rebello et al., 2021; Pham et al., 2022)
<i>Desulfovibrio desulfuricans</i> , <i>Oceanobacillus profundus</i> , <i>Pseudomonas putida</i> , <i>Staphylococcus epidermidis</i>	Zinc (Zn)	(Afzal et al., 2017; Singh et al., 2022)
<i>Pseudomonas alcaliphila</i> , <i>Pseudomonas aeruginosa</i> , <i>Stenotrophomonas maltophilia</i>	Chromium (Cr)	(Ray and Ray 2009; Sharma et al., 2021)
<i>Pseudomonas aeruginosa</i> , <i>Vibrio parahaemolyticus</i>	Mercury (Hg)	Rebello et al. (2021)
<i>Micrococcus luteus</i> , <i>Pseudomonas azotoformans</i>	Copper (Cu)	Selvi et al. (2019)
<i>Klebsiella variicola</i> , <i>Pseudomonas cepacia</i>	Nickel (Ni)	(Abdel-Monem et al., 2010; Afzal et al., 2017).

roots (Mathé et al., 2019).

5.3. Organic manures and soil remediation

The use of organic materials such as biochar and peat moss in the reclamation of soil contaminated with HM has been reported. The former has been observed to reduce the bioaccumulation of toxic HMs within food crops, aside from their benefits in enhancing crop growth. Nawab et al. (2018), utilized and studied the ability of biochar, farmyard manure, and peat moss on agricultural soil that has been impacted by mining activities. Their study focused on utilizing these organic manures to immobilize toxic HMs specifically Ni, Cr, As, Zn, Cd and Pb and to reduce the bioaccumulation of these in chilli and pea. It was found that the use of these organic amendments significantly decreased the bioavailability of toxic HMs in the soil. Also, it was observed that the application of these organic substances minimized the intake of toxic HMs and the risk involved. However, biochar was found to have the most effect in immobilizing toxic HMs.

Ghani et al. (2022b), compared the prospects of orange peel-derived biochar and poultry manure in reducing the bioavailability of toxic HMs when applied to degraded agricultural soil and to the okra plant. It was observed that these organic substances reduced Cd and Ni availability and uptake in the plant and increased the plant biomass. However, when compared with poultry manure, it was found that the use of orange peel biochar is a more feasible method with prospects of immobilizing toxic HMs. From the study of Nawab et al. (2019), which focused on determining the influence of different organic geo-sorbents on *Spinacia oleracea* grown in chromite mine-degraded soil, it was observed that organic substances like biochar, farmyard manure, and peat moss immobilized the concentrations of the Potentially Toxic Elements (PTE) in mine-degraded soil, caused a significant decrease in the bioaccumulation of Cr, As, Ni, Cd, Zn, and Pb, and also increased the major nutrient contents in spinach.

6. Prospects of soil bioremediation and the reclaim of polluted soil for agriculture

The soil remediation process involves the detoxification of hazardous substances in the soil; hence, healthy soil is obtained after a successful restoration of contaminated soil from HMs. This in turn results in an increase in crop production, crop yield, and consequently, food security and safety. The non-invasive, eco-friendly, and sustainable advantages of bioremediation make it applicable and suitable for the elimination of contaminants such as HMs. Bioremediation has the prospect of

effectively reclaiming contaminated soil environments inexpensively. Nevertheless, a lack of adequate skills and proficiency on the consequences of divers' environmental factors on biotransformation and biodegradation questions the certainty of this remediation technique.

Several microbes with biotransformation potentials are waiting to be explored, but insufficient information about these microorganisms and the natural role they play in the environment can hinder their utilization. For example, deciphering the diversity and functional attributes of the microbial community in an HM contaminated soil environment is vital to understanding microbial degraders and their attributes (biologically and chemically) that can be optimized in the development of suitable bioremediation techniques, thereby preserving the lifelong sustainability of natural habitats (Babalola et al., 2021; Abboud 2022; Omotayo et al., 2022).

6.1. Reclaimed polluted soil, agriculture and the sustainable development goals (SDG's)

The role of soil and the rhizosphere microbiome in contributing to the UN Sustainable Development Goals cannot be overemphasized as soils play a vital role in delivering the SDGs (Keesstra et al., 2018; Bouma 2019; Bouma et al., 2019; Omotayo and Babalola 2021). In their study, Keesstra et al. (2016), explored the role of soils in delivering the SDGs through a series of short essays focusing on the SDGs related to food security, water scarcity, climate change, biodiversity loss, and health threats. They used an approach that mapped the functions provided by soils to five SDGs. Using a similar approach, Smith et al. (2019) examined how soil carbon sequestration as a climate mitigation strategy provides co-benefits and trade-offs to the delivery of all SDGs.

Like Keesstra et al. (2016), Smith et al. (2019), first considered the functions provided by the soils and mapped these to Nature's Contributions to People (NCP), with the delivery of these NCP then mapped onto the delivery of the SDGs. The role of soils in contributing, positively to the UN SDGs is described herein. The seven soil functions as defined by the European Commission (Paleari 2017; Heuser 2022) are; (1) biomass production, including agriculture and forestry; (2) storing, filtering, and transforming nutrients, substances, and water; (3) biodiversity pool, such as habitats, species, and genes; (4) physical and cultural environment for humans and human activities; (5) source of raw material; (6) acting as carbon pool; and (7) archive of geological and archaeological heritage.

Interestingly, good and healthy soil has the potential to deliver sustainable agriculture in key areas of the SDGs. For example, to end hunger and poverty according to the Sustainable Development Goals (SDG) 1-No poverty and 2- Zero hunger of the United Nations, agriculture in all spheres, including crop production, is a major strategy. Agriculture does not only create a positive impact on the economies of households but also strengthens those of nations and assists in the eradication of hunger. However, to achieve sustainable crop production, agricultural soil must be free from pollutants and contaminants such as HM.

Additionally, the redemption of agricultural soil from these pollutants also helps in reversing their damaging effects on soil biodiversity, thus reversing land degradation, while protecting, and promoting sustainable use of terrestrial ecosystems in line with SDG 15-Life on the Land of the United Nations. Furthermore, the achievement of SDG 3 (Good health and wellbeing), which is focused on health, cannot be achieved if life on land is not redeemed from toxic metals, as this poisonous substance infiltrates into the food chain, thus causing various health challenges for consumers. Likewise, remediation of the soil from HM has the potential to help prevent life in water from jeopardy (since it stops toxic metals from leaching into the water bodies from the soil) and assist in the achievement of clean water and sanitation (SDG 6- Clean water and sanitation).

7. Adverse impact of HMs on agriculture and food productivity and sustainability

Apart from the impact of HMs on food safety, these pollutants affect sustainable agriculture and crop production.

- Disturbing the soil microbiome thus negatively affecting soil health and quality:

Certain HMs, such as mercury (Hg) are hazardous to the soil microbial communities. According to [Salam et al. \(2019\)](#), mercury contamination causes selective pressure on the soil microbial communities, thereby affecting their population as well as the physicochemical properties of the soil. The unfavourable impact of cadmium on the population of bacteria and fungi in the soil consequently affects the soil's health and quality ([Alsabhan et al., 2022](#)). According to [Singh and Kalamdhad \(2011\)](#), high concentrations of HM are harmful to plants and soil as they exhibit toxic effects on soil microorganisms by tampering with major microbial and metabolic processes, thus hampering the diversity of soil microbes. [Yan et al. \(2020a\)](#), reported an alteration of the composition of soil microbial communities as well as the activity of these microbes because of HM contamination. In their study, [Singh and Kalamdhad \(2011\)](#) emphasized that the soil ecology is jeopardized by HM consequently impacting the health of organisms within the ecosystem. Indirectly, HM inhibits the activities of soil enzymes, by hindering the activities of microbes synthesizing enzymes thus resulting in the loss of soil organic matter and an alteration of the nutrient cycle ([Wang et al., 2007](#)). Because of HM, degrading soil health eventually leads to quality loss.

- By impacting plant/crop growth and development thus jeopardizing crop yield:

Cr, Pb, Cd, and As are examples of HMs that are most known for inhibiting plant growth and subsequently affecting its yield. In their study, [Dotaniya et al. \(2014\)](#), found Cr to negatively affect root elongation and germination of wheat, thus resulting in a drastic reduction in crop yield. Pb is a threat to early seedling growth, germination, and total protein content ([Hussain et al., 2013](#)). In barley, Cd is a known threat to proper growth and development, thus affecting its productivity, this is evident from the study of [Gubrelay et al. \(2013\)](#), [Kintlová et al. \(2021\)](#) and [Ermoshin et al. \(2021\)](#), where root shortening, decreased length of shoot, inhibition of barley seedlings, and overall growth retardation were observed.

8. Conclusion and recommendations

In this review, the ubiquity and prevalence of HM in the environment were discussed in addition to the identification of the sources, and the various effects of these on the environment and health. The impact of these pollutants on agricultural production, ranging from the negative consequences on the soil microbiome, soil quality, and plant growth process to their long-term impact on soil microbial diversity and human health due to their infiltration into the food chain, cannot be overlooked. The significant contribution of anthropogenic activities such as mining to the presence of HMs in the environment and soil was identified and highlighted. To achieve the Sustainable Development Goals of the United Nations targeted at ending poverty, hunger, preservation of life on land, and achieving clean water (SDG 1, 2, 3, 6, and 15), the menace posed by soil HMs must be tackled. This study evaluated bioremediation strategies that use natural products such as plants and microorganisms to remove HM-contaminated soils due to their eco-friendly nature. Practical and environmentally friendly phytoremediation techniques can accomplish the removal of HM from soil. The risk of HM pollution could also be reduced via "in-situ" and "ex-situ" bioremediation, which converts poisonous HMs into less hazardous forms. Phytoremediation is

a widely accepted method of recovering HM-contaminated soil, phytoremediation offers numerous advantages over alternative physical or chemical approaches. It is impossible to ignore the possibility of bioremediation as a less costly method of cleansing contaminated soil. Our review's findings necessitate further research to understand the functional traits and diversity of microbes in HM-contaminated soil, which will facilitate the identification and understanding of microbial degraders for the development of suitable bioremediation inoculants, thereby promoting the sustainability of natural habitats. Additionally, further research to determine whether hyperaccumulators or microorganisms are better suited for the removal of particular hazardous HMs is strongly advised.

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Ethics approval

Not applicable.

10. Consent to participate

Not applicable.

11. Consent to publish

Not applicable.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

- Abboud, N., 2022. The promise of Bioremediation. *Environments. Pollution, Water.* <https://www.ecomena.org/bioremediation/>.

- Abdel-Monem, M., Al-Zubeiry, A., Al-Gheethi, A., 2010. Biosorption of nickel by *Pseudomonas cepacia* 120S and *Bacillus subtilis* 117S. *Water Sci. Technol.* 61, 2994–3007.
- Abdullah, K., Kaushal, J.B., Takkar, S., Sharma, G., Alsafwani, Z.W., Pothuraju, R., Batra, S.K., Siddiqui, J.A., 2024. Copper metabolism and cuproptosis in human malignancies: unraveling the complex interplay for therapeutic insights. *Heliyon*, E27496.
- AEC, U., 2000. In-situ Electrokinetic Remediation of Metal Contaminated Soils-Technology Status Report. US Army Environmental Center. Report Number: SFIM-AEC-ET-CR-99022.
- Afzal, A.M., Rasool, M.H., Waseem, M., Aslam, B., 2017. Assessment of heavy metal tolerance and biosorptive potential of *Klebsiella varicola* isolated from industrial effluents. *Amb. Express* 7, 1–9.
- Ahamad, A., Raju, N.J., Madhav, S., Gossel, W., Ram, P., Wycisk, P., 2021. Potentially toxic elements in soil and road dust around Sonbhadra industrial region, Uttar Pradesh, India: source apportionment and health risk assessment. *Environ. Res.* 202, 111685.
- Alford, É.R., Pilon-Smits, E.A., Fakra, S.C., Paschke, M.W., 2012. Selenium hyperaccumulation by *Astragalus* (Fabaceae) does not inhibit root nodule symbiosis. *Am. J. Bot.* 99, 1930–1941.
- Alsabhan, A.H., Perveen, K., Alwadi, A.S., 2022. Heavy metal content and microbial population in the soil of Riyadh Region, Saudi Arabia. *J. King Saud Univ. Sci.* 34, 101671.
- Alur, A., Phillips, J., Xu, D., 2024. Effects of hexavalent chromium on mitochondria and their implications in carcinogenesis. *Journal of Environmental Science and Health Part C*, 1–17.
- Antonkiewicz, J., Kołodziej, B., Bielińska, E.J., Witkiewicz, R., Tabor, S., 2018. Using *Jesumalea Artichoke* to extract heavy metals from municipal sewage sludge amended soil. *Pol. J. Environ. Stud.* 27.
- Aposhian, H.V., Avram, M.D., Tsapralis, G., Chowdhury, U.K., 2006. Arsenic: the king of poisons, the poisons of kings, and the bane of investigators, 1680–1680. In: *Chemical Research in Toxicology*. AMER CHEMICAL SOC, 1155 16TH ST, NW, WASHINGTON, DC 20036 USA.
- Aslam, M., Aslam, A., Sheraz, M., Ali, B., Ulhassan, Z., Najeeb, U., Zhou, W., Gill, R.A., 2021. Lead toxicity in cereals: mechanistic insight into toxicity, mode of action, and management. *Front. Plant Sci.* 11, 2248.
- Ayangbenro, A.S., Babalola, O.O., 2017. A new strategy for heavy metal polluted environments: a review of microbial biosorbents. *Int. J. Environ. Res. Publ. Health* 14, 94.
- Azarakhsh, M., Asrar, Z., Mansouri, H., 2015. Effects of seed and vegetative stage cysteine treatments on oxidative stress response molecules and enzymes in *Ocimum basilicum* L. under cobalt stress. *J. Soil Sci. Plant Nutr.* 15, 651–662.
- Babalola, O.O., Omatayo, O.P., Ighehon, N.O., 2021. Survey of maize rhizosphere microbiome using shotgun metagenomics. *Microbiology Resource Announcements* 10. <https://doi.org/10.1128/mra.01309-20>.
- Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M.R., Sadeghi, M., 2021. Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Front. Pharmacol.* 12.
- Bani, A., Pavlova, D., Benizi, E., Shallari, S., Miho, L., Meco, M., Shahu, E., Reeves, R., Echevarria, G., 2018. Relationship between the Ni hyperaccumulator *Alyssum murale* and the parasitic plant *Orobancha nowackiana* from serpentine in Albania. *Ecol. Res.* 33, 549–559.
- Bernstam, L., Nriagu, J., 2000. Molecular aspects of arsenic stress. *J. Toxicol. Environ. Health B Crit. Rev.* 3, 293–322.
- Bhalerao, S.A., Sharma, A.S., Poojari, A.C., 2015. Toxicity of nickel in plants. *International Journal of Pure and Applied Bioscience* 3, 345–355.
- Bhatti, Z.I., Ishtiaq, M., Khan, S.A., Nawab, J., Ghani, J., Ullah, Z., Khan, S., Baig, S.A., Muhammad, I., Din, Z.U., 2022. Contamination level, source identification and health risk assessment of potentially toxic elements in drinking water sources of mining and non-mining areas of Khyber Pakhtunkhwa, Pakistan. *J. Water Health* 20, 1343–1363.
- Biswas, S., Ganesan, M., 2024. Current perspectives of ACR3 (arsenite efflux system) toward the reduction of arsenic accumulation in plants. *Journal of Crop Science and Biotechnology* 1–17.
- Boffetta, P., 1993. Carcinogenicity of trace elements with reference to evaluations made by the International Agency for Research on Cancer. *Scand. J. Work. Environ. Health* 67–70.
- Bouma, J., 2019. Soil security in sustainable development. *Soil Systems* 3, 5.
- Bouma, J., Montanarella, L., Evanylo, G., 2019. The challenge for the soil science community to contribute to the implementation of the UN Sustainable Development Goals. *Soil Use Manag.* 35, 538–546.
- Brdar-Jokanović, M., 2020. Boron toxicity and deficiency in agricultural plants. *Int. J. Mol. Sci.* 21, 1424.
- Broadhurst, C.L., Chaney, R.L., 2016. Growth and metal accumulation of an *Alyssum murale* nickel hyperaccumulator ecotype co-cropped with *Alyssum montanum* and perennial ryegrass in serpentine soil. *Front. Plant Sci.* 7, 451.
- Brooks, R., Robinson, B., Howes, A., Chiarucci, A., 2001. An evaluation of *Berkheya coddii* Roessler and *Alyssum bertolonii* Desv. for phytoremediation and phytomining of nickel. *South Afr. J. Sci.* 97, 558–560.
- Bruins, M.R., Kapil, S., Oehme, F.W., 2000. Microbial resistance to metals in the environment. *Ecotoxicol. Environ. Saf.* 45, 198–207.
- Brusseau, M.L., 2019. Soil and groundwater remediation. In: *Environmental and Pollution Science*. Elsevier, pp. 329–354.
- Budak, T., 2013. Removal of heavy metals from wastewater using synthetic ion exchange resin. *Asian J. Chem.* 25.
- Carroll, M., Evans, J., Pashley, V., Prowse, T., 2021. Tracking Roman lead sources using lead isotope analysis. A case study from the imperial rural estate at Vagnari (Puglia, Italy). *J. Archaeol. Sci.: Report* 36, 102821.
- Cauwenbergh, L.V., 1987. Electrokinetics. In: TO-97-03. Ground-Water Remediation Technologies Analysis Center.
- Cenova, A., Nestorovska, M., Crcarevska, M.S., Mihailova, L., Shalabalija, D., Dodov, M. G., 2022. Evaluation of antioxidant properties of herbal mixture and CBD oil for the treatment of chronic wound. *Macedonian pharmaceutical bulletin*.
- Charkiewicz, A.E., Backstrand, J.R., 2020. Lead toxicity and pollution in Poland. *Int. J. Environ. Res. Publ. Health* 17, 4385.
- Chekroun, K.B., Sánchez, E., Baghour, M., 2014. The role of algae in bioremediation of organic pollutants. *Journal Issues ISSN* 2360, 8803.
- Comis, D., 1996. Green remediation: using plants to clean the soil. *J. Soil Water Conserv.* 51, 184–187.
- Dahman, Y., 2017. Nanotechnology and Functional Materials for Engineers. Elsevier.
- DalCorso, G., Fasani, E., Manara, A., Visioli, G., Furini, A., 2019. Heavy metal pollution: state of the art and innovation in phytoremediation. *Int. J. Mol. Sci.* 20, 3412.
- Dao, M.T., Nguyen, T.T., Nguyen, X.D., La, D.D., Nguyen, D.D., Chang, S., Chung, W., Nguyen, V.K., 2020. Toxic metal adsorption from aqueous solution by activated biochars produced from macadamia nutshell waste. *Sustainability* 12, 7909.
- Das, K.K., Reddy, R.C., Bagoji, I.B., Das, S., Bagali, S., Mullur, L., Khodnapur, J.P., Biradar, M., 2019. Primary concept of nickel toxicity—an overview. *J. Basic Clin. Physiol. Pharmacol.* 30, 141–152.
- Dasgupta, S., Satvat, P.S., Mahindrakar, A.B., 2011. Ability of *Cicer arietinum* (L.) for bioremoval of lead and chromium from soil. *International Journal of Technology and Engineering System* 24, 338–341.
- De Lillo, A., Cardì, M., Landi, S., Esposito, S., 2018. Mechanism(s) of action of heavy metals to investigate the regulation of plastidic glucose-6-phosphate dehydrogenase. *Sci. Rep.* 8, 13481.
- de Souza Neto, H.F., da Silveira Pereira, W.V., Dias, Y.N., de Souza, E.S., Teixeira, R.A., de Lima, M.W., Ramos, S.J., do Amarante, C.B., Fernandes, A.R., 2020. Environmental and human health risks of arsenic in gold mining areas in the eastern Amazon. *Environ. Pollut.* 265, 114969.
- Del Real, A.P., Pérez-Sanz, A., García-Gonzalo, P., Castillo-Michel, H., Gismera, M., Lobo, M., 2020. Evaluating Cr behaviour in two different polluted soils: mechanisms and implications for soil functionality. *J. Environ. Manag.* 276, 111073.
- Demetriou, A., Pashalidis, I., 2012. Adsorption of boron on iron-oxide in aqueous solutions. *Desalination Water Treat.* 37, 315–320.
- Dhane, A.S., Sarode, S.C., Sarode, G.S., Sharma, N.K., 2024. Rise in arsenic pollution and oral cancer: a call for action. *Oral Oncology Reports*, 100238.
- Dirbaba, N.B., Yan, X., Wu, H., Colebrooke, L.L., Wang, J., 2018. Occurrences and ecotoxicological risk assessment of heavy metals in surface sediments from Awash River Basin, Ethiopia. *Water* 10, 535.
- Dosuna-Rodríguez, I., Gaigneaux, E.M., 2012. Glycerol acetylation catalysed by ion exchange resins. *Catal. Today* 195, 14–21.
- Dotaniya, M.L., Das, H., Meena, V.D., 2014. Assessment of chromium efficacy on germination, root elongation, and coleoptile growth of wheat (*Triticum aestivum* L.) at different growth periods. *Environ. Monit. Assess.* 186, 2957–2963.
- Dowling, D.N., Doty, S.L., 2009. Improving phytoremediation through biotechnology. *Curr. Opin. Biotechnol.* 20, 204–206.
- Eldidamony, A., Moustafa, G., Mead, H., Abdel Hafez, M., Omran, B., 2021. Genotoxic and clinicopathological implications of heliotropium curassavicum extracts in a comparative toxicological study with zinc phosphide in male rats. *Adv. Anim. Vet. Sci.* 9, 203–214.
- Elleuch, J., Amor, F.B., Chaaben, Z., Frikha, F., Michaud, P., Fendri, I., Abdelkafi, S., 2021. Zinc biosorption by *Dunaliella* sp. AL-1: mechanism and effects on cell metabolism. *Sci. Total Environ.* 773, 145024.
- Elyamine, A.M., Kan, J., Meng, S., Tao, P., Wang, H., Hu, Z., 2021. Aerobic and anaerobic bacterial and fungal degradation of pyrene: mechanism pathway including biochemical reaction and catabolic genes. *Int. J. Mol. Sci.* 22, 8202.
- Engwa, G.A., Ferdinand, P.U., Nwalo, F.N., Unachukwu, M.N., 2019. Mechanism and health effects of heavy metal toxicity in humans. Poisoning in the modern world-new tricks for an old dog 10.
- Ermoshin, A., Sinenko, O., Nikkonen, I., Novikov, V., Kiseleva, I., 2021. Extracts of xylotrophic fungi reduce toxic effects of cadmium ions in barley. In: *AIP Conference Proceedings*. AIP Publishing LLC, 030006.
- Esmaili, H., Foroutan, R., 2015. Investigation into ion exchange and adsorption methods for removing heavy metals from aqueous solutions. *Int. J. Biol. Pharm. Allied Sci.* 4, 620–629.
- Fashola, M.O., Ngole-Jeme, V.M., Babalola, O.O., 2016. Heavy metal pollution from gold mines: environmental effects and bacterial strategies for resistance. *Int. J. Environ. Res. Publ. Health* 13, 1047.
- Feng, Y., Gong, J.-L., Zeng, G.-M., Niu, Q.-Y., Zhang, H.-Y., Niu, C.-G., Deng, J.-H., Yan, M., 2010. Adsorption of Cd (II) and Zn (II) from aqueous solutions using magnetic hydroxyapatite nanoparticles as adsorbents. *Chem. Eng. J.* 162, 487–494.
- Franchitto, N., Gandia-Mailly, P., Georges, B., Galinier, A., Telmon, N., Ducassé, J.L., Rougé, D., 2008. Acute copper sulphate poisoning: a case report and literature review. *Resuscitation* 78, 92–96.
- Gallego, S., Benavides, M., Tomaro, M., 2002. Involvement of an antioxidant defence system in the adaptive response to heavy metal ions in *Helianthus annuus* L. cells. *Plant Growth Regul.* 36, 267–273.
- Gangwar, C., Choudhari, R., Chauhan, A., Kumar, A., Singh, A., Tripathi, A., 2019. Assessment of air pollution caused by illegal e-waste burning to evaluate the human health risk. *Environ. Int.* 125, 191–199.

- Gao, X., Jiang, L., Mao, Y., Yao, B., Jiang, P., 2021. Progress, challenges, and perspectives of bioleaching for recovering heavy metals from mine tailings. *Adsorpt. Sci. Technol.* 2021.
- Genchi, G., Carocci, A., Lauria, G., Sinicropi, M.S., Catalano, A., 2020. Nickel: human health and environmental toxicology. *Int. J. Environ. Res. Publ. Health* 17, 679.
- Ghani, J., Nawab, J., Faiq, M.E., Ullah, S., Alam, A., Ahmad, I., Ali, S.W., Khan, S., Ahmad, I., Muhammad, A., 2022a. Multi-geostatistical analyses of the spatial distribution and source apportionment of potentially toxic elements in urban children's park soils in Pakistan: a risk assessment study. *Environ. Pollut.* 311, 119961.
- Ghani, J., Nawab, J., Khan, S., Khan, M.A., Ahmad, I., Ali, H.M., Siddiqui, M.H., Funari, V., Dinelli, E., 2022b. Organic amendments minimize the migration of potentially toxic elements in soil-plant system in degraded agricultural lands. *Biomass Conversion and Biorefinery* 1–19.
- Ghani, J., Nawab, J., Ullah, Z., Rafiq, N., Hasan, S.Z., Khan, S., Shah, M., Almutairi, M.H., 2023. Multivariate statistical methods and GIS-based evaluation of potable water in urban children's parks due to potentially toxic elements contamination: a children's health risk assessment study in a developing country. *Sustainability* 15, 13177.
- Giacon, G., Boon, K., 2021. Cobalt toxicity: a preventable and treatable cause for possibly life threatening cardiomyopathy. *N. Z. Med. J.* 134, 103–108.
- Greipsson, S., 2011. Phytoremediation. *Nature Education Knowledge* 3 (7).
- Grióni, S., Agnoli, C., Krogh, V., Pala, V., Rinaldi, S., Vinceti, M., Contiero, P., Vescovi, L., Malavolti, M., Sieri, S., 2019. Dietary cadmium and risk of breast cancer subtypes defined by hormone receptor status: a prospective cohort study. *Int. J. Cancer* 144, 2153–2160.
- Gryndler, M., Rohlenová, J., Kopecký, J., Matucha, M., 2008. Chloride concentration affects soil microbial community. *Chemosphere* 71, 1401–1408.
- Gubrelay, U., Agnihotri, R.K., Singh, G., Kaur, R., Sharma, R., 2013. Effect of heavy metal Cd on some physiological and biochemical parameters of Barley (*Hordeum vulgare* L.). *Intl. J. Agric. Crop Sci.* 5, 2743.
- Gummin, D.D., Mowry, J.B., Beuhler, M.C., Spyker, D.A., Brooks, D.E., Dibert, K.W., Rivers, L.J., Pham, N.P., Ryan, M.L., 2020. 2019 Annual report of the American Association of poison control centers' National Poison Data System (NPDS): 37th annual report. *Clin. Toxicol.* 58, 1360–1541.
- Guzzi, G., Ronchi, A., Pigatto, P., 2021. Toxic effects of mercury in humans and mammals. *Chemosphere* 263, 127990.
- Hadrup, N., Frederiksen, M., Sharma, A.K., 2021. Toxicity of boric acid, borax and other boron containing compounds: a review. *Regul. Toxicol. Pharmacol.* 121, 104873.
- Haider, F.U., Liqun, C., Coulter, J.A., Cheema, S.A., Wu, J., Zhang, R., Wenjun, M., Farooq, M., 2021. Cadmium toxicity in plants: impacts and remediation strategies. *Ecotoxicol. Environ. Saf.* 211, 111887.
- Harshitha, P., Bose, K., Souza, H.S., 2024. Influence of lead-induced toxicity on the inflammatory cytokines. *Toxicology*, 153771.
- Hengstler, J.G., Bolm-Audorf, U., Faldum, A., Janssen, K., Reifenrath, M., Götte, W., Jung, D., Mayer-Popken, O., Fuchs, J., Gebhard, S., Bienfait, H.G., Schlink, K., Dietrich, C., Faust, D., Epe, B., Oesch, F., 2003. Occupational exposure to heavy metals: DNA damage induction and DNA repair inhibition prove co-exposures to cadmium, cobalt and lead as more dangerous than hitherto expected. *Carcinogenesis* 24, 63–73.
- Heuser, I., 2022. Soil governance in current European union law and in the European green deal. *Soil Security* 6, 100053.
- Hu, R., Zhang, Z., Lin, L., Liao, M.a., Tang, Y., Liang, D., Xia, H., Wang, J., Wang, X., Lv, X., 2019. Intercropping with hyperaccumulator plants decreases the cadmium accumulation in grape seedlings. *Acta Agric. Scand. Sect. B Soil Plant Sci* 69, 304–310.
- Huang, F., Liu, B., Yu, Y., Lv, L., Luo, X., Yin, F., 2022. Heavy metals in road dust across China: occurrence, sources and health risk assessment. *Bull. Environ. Contam. Toxicol.* 109, 323–331.
- Hussain, A., Abbas, N., Arshad, F., Akram, M., Khan, Z.I., Ahmad, K., Mansha, M., Mirzaei, F., 2013. Effects of Diverse Doses of Lead (Pb) on Different Growth Attributes of Zea-Mays L.
- Hussain, M., Kaousar, R., Lan, Y., 2024. Zinc-oxide nanoparticles ameliorated the phytotoxic hazards of cadmium toxicity in maize plants by regulating primary metabolites and antioxidants activity. *Front. Plant Sci.* 15, 1346427.
- Hussain, S., Khan, M., Sheikh, T.M.M., Mumtaz, M.Z., Chohan, T.A., Shamim, S., Liu, Y., 2022. Zinc essentiality, toxicity, and its bacterial bioremediation: a comprehensive insight. *Front. Microbiol.* 1912.
- Hyun, H.R., Yoon, H., Lyou, E.S., Kim, J.J., Kwon, S.Y., Lee, T.K., 2021. Short-term legacy effects of mercury contamination on plant growth and nifH-harboring microbial community in rice paddy soil. *Microb. Ecol.* 1–10.
- IARC, 1990. Chromium, nickel and welding. *IARC Monogr. Eval. Carcinog. Risk Chem. Humans*.
- Ilyas, M.Z., Sa, K.J., Ali, M.W., Lee, J.K., 2024. Toxic effects of lead on plants: integrating multi-omics with bioinformatics to develop Pb-tolerant crops. *Planta* 259, 18.
- Izah, S.C., Inyang, I.R., Angaye, T.C., Okowa, I.P., 2016. A review of heavy metal concentration and potential health implications of beverages consumed in Nigeria. *Toxics* 5, 1.
- Jacob, J.M., Karthik, C., Saratale, R.G., Kumar, S.S., Prabakar, D., Kadirvelu, K., Pugazhendhi, A., 2018. Biological approaches to tackle heavy metal pollution: a survey of literature. *J. Environ. Manag.* 217, 56–70.
- Jahromi, N.S.M., Jonoubi, P., Majd, A., Dehghani, M., 2019. Investigating the anatomy of the halophyte *Salsola crassa* and the impact of industrial wastewater on its vegetative and generative structures. *Turk. J. Bot.* 43, 785–797.
- Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B., Beeregowda, K.N., 2014. Toxicity, mechanism and health effects of some heavy metals. *Interdiscipl. Toxicol.* 7, 60.
- Jobby, R., Jha, P., Yadav, A.K., Desai, N., 2018. Biosorption and biotransformation of hexavalent chromium [Cr (VI)]: a comprehensive review. *Chemosphere* 207, 255–266.
- Kabeya, F.I., Pongrac, P., Lange, B., Faucon, M.-P., Van Elteren, J.T., Sala, M., Selih, V.S., Eeckhoudt, E.V., Verbruggen, N., 2018. Tolerance and accumulation of cobalt in three species of *Haumaniastrum* and the influence of copper. *Environ. Exp. Bot.* 149, 27–33.
- Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., Aryal, N., 2022. Phytoremediation: mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances* 8, 100203.
- Kaur, H., Srivastava, S., Goyal, N., Walia, S., 2024. Behavior of zinc in soils and recent advances on strategies for ameliorating zinc phyto-toxicity. *Environ. Exp. Bot.*, 105676.
- Keesstra, S., Mol, G., De Leeuw, J., Okx, J., Molenaar, C., De Cleen, M., Visser, S., 2018. Soil-related sustainable development goals: four concepts to make land degradation neutrality and restoration work. *Land* 7, 133.
- Keesstra, S.D., Bouma, J., Wallinga, J., Titttonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J.N., Pachepsky, Y., Van Der Putten, W.H., 2016. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soils*.
- Khan, M.I.R., Jahan, B., AlAjmi, M.F., Rehman, M.T., Iqbal, N., Irfan, M., Sehar, Z., Khan, N.A., 2021. Crosstalk of plant growth regulators protects photosynthetic performance from arsenic damage by modulating defense systems in rice. *Ecotoxicol. Environ. Saf.* 222, 112535.
- Khan, S., Masoodi, T.H., Pala, N.A., Murtaza, S., Mugloo, J.A., Sofi, P.A., Zaman, M.U., Kumar, R., Kumar, A., 2023. Phytoremediation prospects for restoration of contamination in the natural ecosystems. *Water* 15, 1498.
- Khelifi, F., Mokadem, N., Liu, G., Yousaf, B., Zhou, H., Ncibi, K., Hamed, Y., 2022. Occurrence, contamination evaluation and health risks of trace metals within soil, sediments and tailings in southern Tunisia. *Int. J. Environ. Sci. Technol.* 19, 6127–6140.
- Kintlová, M., Vrána, J., Hobza, R., Blavet, N., Hudzieczek, V., 2021. Transcriptome response to cadmium exposure in barley (*hordeum vulgare* L.). *Front. Plant Sci.* 12.
- Kinuthia, G.K., Ngure, V., Beti, D., Lugalia, R., Wangila, A., Kamau, L., 2020. Levels of heavy metals in wastewater and soil samples from open drainage channels in Nairobi, Kenya: community health implication. *Sci. Rep.* 10, 8434.
- Koller, C., Patrick, J., Rose, R., Offler, C., MacFarlane, G., 2008. Arsenic and heavy metal accumulation by *Pteris vittata* L. and *P. umbrosa* R. *Br. Bull. Environ. Contam. Toxicol.* 80, 128–133.
- Kumar, M., Seth, A., Singh, A.K., Rajput, M.S., Sikandar, M., 2021. Remediation strategies for heavy metals contaminated ecosystem: a review. *Environmental and Sustainability Indicators* 12, 100155.
- Kumar, V., Kumar, P., Singh, J., 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. *Int. J. Phytoremediation* 22, 392–403.
- Lakherwal, D., 2014. Adsorption of heavy metals: a review. *Int. J. Environ. Res. Dev.* 4, 41–48.
- Leyssens, L., Vinck, B., Van Der Straeten, C., Wuyts, F., Maes, L., 2017. Cobalt toxicity in humans—a review of the potential sources and systemic health effects. *Toxicology* 387, 43–56.
- Li-qun, W., Lei, L., Yi-bing, M., Dong-pu, W., Luo, H., 2009. In situ immobilization remediation of heavy metals-contaminated soils: a review. *Yingyong Shengtai Xuebao* 20.
- Li, J., Hashimoto, Y., Riya, S., Terada, A., Hou, H., Shibagaki, Y., Hosomi, M., 2019. Removal and immobilization of heavy metals in contaminated soils by chlorination and thermal treatment on an industrial-scale. *Chem. Eng. J.* 359, 385–392.
- Li, Q., Liao, J., Lei, C., Shi, J., Zhang, H., Han, Q., Guo, J., Hu, L., Li, Y., Pan, J., 2021. Metabolomics analysis reveals the effect of copper on autophagy in myocardia of pigs. *Ecotoxicol. Environ. Saf.* 213, 112040.
- Lim, M., Guak, S., Cheong, N.Y., Song, Y.C., Ho, K.-F., Nakai, S., Lung, S.-C.C., Tantrakarnapa, K., Lee, K., 2022. Children's exposures to boron and biocides from slime products in Asian regions. *J. Expo. Sci. Environ. Epidemiol.* 32, 103–111.
- Lindblom, S.D., Fakra, S.C., Landon, J., Schulz, P., Tracy, B., Pilon-Smits, E.A., 2013. Inoculation of *Astragalus racemosus* and *Astragalus convallarius* with selenium-hyperaccumulator rhizosphere fungi affects growth and selenium accumulation. *Planta* 237, 717–729.
- Liu, C., Lin, H., Li, B., Dong, Y., Yin, T., 2020. Responses of microbial communities and metabolic activities in the rhizosphere during phytoremediation of Cd-contaminated soil. *Ecotoxicol. Environ. Saf.* 202, 110958.
- Lombi, E., Hamon, R., 2005. Remediation of polluted soils. *Encyclopedia of Soils in the Environment* 4, 379–385.
- Lozano, M., Murcia, M., Soler-Blasco, R., Casas, M., Zubero, B., Riutort-Mayol, G., Gil, F., Olmedo, P., Grimalt, J.O., Amorós, R., 2022. Exposure to metals and metalloids among pregnant women from Spain: levels and associated factors. *Chemosphere* 286, 131809.
- Lucchini, R.G., Kotelchuck, D., Grandjean, P., 2015. Principles for prevention of the toxic effects of metals. In: *Handbook on the Toxicology of Metals*. Elsevier, pp. 507–528.
- Madhav, S., Mishra, R., Kumari, A., Srivastav, A., Ahamad, A., Singh, P., Ahmed, S., Mishra, P., Sillanpää, M., 2024. A review on sources identification of heavy metals in soil and remediation measures by phytoremediation-induced methods. *Int. J. Environ. Sci. Technol.* 21, 1099–1120.
- Mahajan, P., Kaushal, J., 2018. Role of phytoremediation in reducing cadmium toxicity in soil and water. *J. Toxicol.* 2018.
- Mahey, S., Kumar, R., Sharma, M., Kumar, V., Bhardwaj, R., 2020. A critical review on toxicity of cobalt and its bioremediation strategies. *SN Appl. Sci.* 2, 1279.

- Malar, S., Sahi, S.V., Favas, P.J.C., Venkatachalam, P., 2015. Assessment of mercury heavy metal toxicity-induced physiochemical and molecular changes in *Sesbania grandiflora* L. *Int. J. Environ. Sci. Technol.* 12, 3273–3282.
- Maqsood, M., Zahra, N., Kausar, A., Shahzad, S., Batool, A., Naseer, R., 2024. Mercury contamination and its dynamics in soil–plant systems. In: *Mercury Toxicity Mitigation: Sustainable Nexus Approach*. Springer, pp. 45–63.
- Marchioretto, M., Bruning, H., Hien, N.T., Rulkens, W., 2003. Bioleaching and Chemical Leaching of Heavy Metals from Anaerobically Digested Sludge.
- Mathé, C., Fawal, N., Roux, C., Dunand, C., 2019. In silico definition of new ligninolytic peroxidase sub-classes in fungi and putative relation to fungal life style. *Sci. Rep.* 9, 1–14.
- McBride, M.B., Zhou, Y., 2019. Cadmium and zinc bioaccumulation by *Phytolacca americana* from hydroponic media and contaminated soils. *Int. J. Phytoremediation* 21, 1215–1224.
- Mekonnen, K.N., Ambushe, A.A., Chandravanshi, B.S., Redi-Abshiro, M., McGrindle, R.I., 2014. Assessment of potentially toxic elements in Swiss chard and sediments of Akaki River, Ethiopia. *Toxicol. Environ. Chem.* 96, 1501–1515.
- Mishra, R., Singh, E., Kumar, A., Singh, A.K., Madhav, S., Shukla, S.K., Kumar, S., 2023. Metal pollution in marine environment: sources and impact assessment. In: *Metals in Water*. Elsevier, pp. 175–193.
- Moreno-Jiménez, E., Peñalosa, J.M., Esteban, E., Carpena-Ruiz, R.O., 2007. Mercury accumulation and resistance to mercury stress in *Rumex induratus* and *Marrubium vulgare* grown in perlite. *J. Plant Nutr. Soil Sci.* 170, 485–494.
- Muro-González, D.A., Mussali-Galante, P., Valencia-Cuevas, L., Flores-Trujillo, K., Tovar-Sánchez, E., 2020. Morphological, physiological, and genotoxic effects of heavy metal bioaccumulation in *Prosopis laevigata* reveal its potential for phytoremediation. *Environ. Sci. Pollut. Control Ser.* 27, 40187–40204.
- Muszynska, E., Hanus-Fajerska, E., 2015. Why are heavy metal hyperaccumulating plants so amazing? *BioTechnologia. Journal of Biotechnology Computational Biology and Bionanotechnology* 96.
- Nagai, T., Horio, T., Yokoyama, A., Kamiya, T., Takano, H., Makino, T., 2012. Ecological risk assessment of on-site soil washing with iron (III) chloride in cadmium-contaminated paddy field. *Ecotoxicol. Environ. Saf.* 80, 84–90.
- Nawab, J., Ghani, J., Khan, S., Xiaoping, W., 2018. Minimizing the risk to human health due to the ingestion of arsenic and toxic metals in vegetables by the application of biochar, farmyard manure and peat moss. *J. Environ. Manag.* 214, 172–183.
- Nawab, J., Khan, N., Ahmed, R., Khan, S., Ghani, J., Rahman, Z., Khan, F., Wang, X., Muhammad, J., Sher, H., 2019. Influence of different organic geo-sorbents on *Spinacia oleracea* grown in chromite mine-degraded soil: a greenhouse study. *J. Soils Sediments* 19, 2417–2432.
- Nguyen, C., 2003. Rhizodeposition of organic C by plants: mechanisms and controls. *Agronomie* 23, 375–396.
- Nkrumah, P.N., Echevarria, G., Erskine, P.D., van der Ent, A., 2018. Nickel hyperaccumulation in *Antidesma montis-silam*: from herbarium discovery to collection in the native habitat. *Ecol. Res.* 33, 675–685.
- Nowak, B., Rocha, S.F., Aschenbrenner, P., Rechberger, H., Winter, F., 2012. Heavy metal removal from MSW fly ash by means of chlorination and thermal treatment: influence of the chloride type. *Chem. Eng. J.* 179, 178–185.
- Nurfitri, A., Masayuki, S., Koichiro, S., 2017. Phytoremediation of heavy metal-polluted mine drainage by *Eleocharis acicularis*. *Environmental Science Indian Journal* 13, 131.
- Omatayo, O.P., 2022. The role of rhizosphere microbiome in agricultural sustainability. *PONTE International Journal of Science and Research* 78.
- Omatayo, O.P., Babalola, O.O., 2021. Resident rhizosphere microbiome's ecological dynamics and conservation: towards achieving the envisioned sustainable development goals, a review. *International Soil and Water Conservation Research* 9, 127–142.
- Omatayo, O.P., Babalola, O.O., 2023. *Fusarium verticillioides* of maize plant: potentials of propitious phytomicrobiome as biocontrol agents. *Frontiers in Fungal Biology* 4, 1095765.
- Omatayo, O.P., Igiehon, O.N., Babalola, O.O., 2021. Metagenomic study of the community structure and functional potentials in maize rhizosphere microbiome: elucidation of mechanisms behind the improvement in plants under normal and stress conditions. *Sustainability* 13, 8079.
- Omatayo, O.P., Igiehon, O.N., Babalola, O.O., 2022. Microbial genes of agricultural importance in maize rhizosphere unveiled through shotgun metagenomics. *Spanish Journal of Soil Science* 12, 10427.
- Organization, W.H., 1996. Originally published in Guidelines for drinking-water quality. Health criteria and other supporting information 2.
- Pacwa-Plociniczak, M., Plociniczak, T., Yu, D., Kurola, J.M., Sinkkonen, A., Piotrowska-Seget, Z., Romantschuk, M., 2018. Effect of *Silene vulgaris* and heavy metal pollution on soil microbial diversity in long-term contaminated soil. *Water, Air, Soil Pollut.* 229, 1–13.
- Page, M.J., Moher, D., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., 2021. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *Br. Med. J.* 372.
- Palcari, S., 2017. Is the European Union protecting soil? A critical analysis of Community environmental policy and law. *Land Use Pol.* 64, 163–173.
- Parks, J.L., Edwards, M., 2005. Boron in the environment. *Crit. Rev. Environ. Sci. Technol.* 35, 81–114.
- Pearce, K., Snyman, H., Van Heerden, H., Greben, H., Oellermann, R., Water, W., 1995. Bioremediation technology for the treatment of contaminated soil in South Africa. Water research commission, division of water technology. CSIR. WRC Report 95.
- Pham, V.H.T., Kim, J., Chang, S., Chung, W., 2022. Bacterial biosorbents, an efficient heavy metals green clean-up strategy: prospects, Challenges, and Opportunities. *Microorganisms* 10, 610.
- Pohl, A., 2020. Removal of heavy metal ions from water and wastewaters by sulfur-containing precipitation agents. *Water, Air, Soil Pollut.* 231, 503.
- Pourrut, B., Shahid, M., Dumat, C., Winterton, P., Pinelli, E., 2011. Lead uptake, toxicity, and detoxification in plants. *Rev. Environ. Contam. Toxicol.* 213, 113–136.
- Qin, C., Lian, H., Alqahtani, F.M., Ahanger, M.A., 2024. Chromium mediated damaging effects on growth, nitrogen metabolism and chlorophyll synthesis in tomato can be alleviated by foliar application of melatonin and jasmonic acid priming. *Sci. Hortic.* 323, 112494.
- Rahaman, S., Sinha, A.C., Pati, R., Mukhopadhyay, D., 2013. Arsenic contamination: a potential hazard to the affected areas of West Bengal, India. *Environ. Geochem. Health* 35, 119–132.
- Ray, S., Ray, M.K., 2009. Bioremediation of heavy metal toxicity-with special reference to chromium. *Al Ameen J. Med. Sci.* 2, 57–63.
- Raza'i, T.S., Thamrin, T., Nofrizal, N., Amrifo, V., Pardi, H., Putra, I.P., Febrianto, T., Ilhamdy, A.F., 2021. Accumulation of essential (copper, iron, zinc) and non-essential (lead, cadmium) heavy metals in *Caulerpa racemosa*, sea water, and marine sediments of Bintan Island, Indonesia. *F1000Research* 10, 699.
- Rebello, S., Nathan, V.K., Sindhu, R., Binod, P., Awasthi, M.K., Pandey, A., 2021. Bioengineered microbes for soil health restoration: present status and future. *Bioengineered* 12, 12839–12853.
- Reeves, R.D., Baker, A.J., Jaffré, T., Erskine, P.D., Echevarria, G., van der Ent, A., 2018. A global database for plants that hyperaccumulate metal and metalloids trace elements. *New Phytol.* 218, 407–411.
- Rezaeian, M., Tohidi Moghadam, M., Kiaei, M.M., Mahmud Zadeh, H., 2020. The effect of heavy metals on the nutritional value of alfalfa: comparison of nutrients and heavy metals of alfalfa (*medicago sativa*) in industrial and non-industrial areas. *Toxicol. Res.* 36, 183–193.
- Saad, R.F., Kobaiissi, A., Machinet, G., Villemin, G., Echevarria, G., Benizri, E., 2018. Crop rotation associating a legume and the nickel hyperaccumulator *Alyssum murale* improves the structure and biofunctioning of an ultramafic soil. *Ecol. Res.* 33, 799–810.
- Saha, L., Tiwari, J., Buddh, K., Ma, Y., 2021. Recent developments in microbe–plant-based bioremediation for tackling heavy metal-polluted soils. *Front. Microbiol.* 12.
- Salam, A., Rehman, M., Qi, J., Khan, A.R., Yang, S., Zeeshan, M., Ulhassan, Z., Afridi, M. S., Yang, C., Chen, N., 2024. Cobalt stress induces photosynthetic and ultrastructural distortion by disrupting cellular redox homeostasis in maize. *Environ. Exp. Bot.* 217, 105562.
- Salam, L.B., Shomope, H., Umami, Z., Bukar, F., 2019. Mercury contamination imposes structural shift on the microbial community of an agricultural soil. *Bull. Natl. Res. Cent.* 43, 163.
- Sandoval-Pauker, C., Molina-Aguirre, G., Pinter, B., 2021. Status report on copper (I) complexes in photoredox catalysis: photophysical and electrochemical properties and future prospects. *Polyhedron* 199, 115105.
- Saqib, M., Khalifah, A., ur Rehman, A., Altaf, M.A., 2024. Alleviating effects of exogenous melatonin on nickel toxicity in two pepper genotypes. *Sci. Hortic.* 325, 112635.
- Schoderboeck, L., Mühlegger, S., Losert, A., Gausterer, C., Hornek, R., 2011. Effects assessment: boron compounds in the aquatic environment. *Chemosphere* 82, 483–487.
- Selvi, A., Rajasekar, A., Theerthagiri, J., Ananthaselvam, A., Sathishkumar, K., Madhavan, J., Rahman, P.K., 2019. Integrated remediation processes toward heavy metal removal/recovery from various environments-a review. *Front. Environ. Sci.* 7, 66.
- Setia, R., Dhaliwal, S.S., Singh, R., Kumar, V., Taneja, S., Kukal, S.S., Pateriya, B., 2021. Phytoavailability and human risk assessment of heavy metals in soils and food crops around Sutlej river, India. *Chemosphere* 263, 128321.
- Seydi, E., Pourahmad, J., 2023. The effect of mercury on the mitochondria. In: *Mitochondrial Intoxication*. Elsevier, pp. 547–555.
- Sharma, N., Sodhi, K.K., Kumar, M., Singh, D.K., 2021. Heavy metal pollution: insights into chromium eco-toxicity and recent advancement in its remediation. *Environ. Nanotechnol. Monit. Manag.* 15, 100388.
- Sharma, R.K., Agrawal, M., 2005. Biological effects of heavy metals: an overview. *J. Environ. Biol.* 26, 301–313.
- Shaw, J., Ernakovich, J., Judy, J., Farrell, M., Whatmuff, M., Kirby, J., 2020. Long-term effects of copper exposure to agricultural soil function and microbial community structure at a controlled and experimental field site. *Environ. Pollut.* 263, 114411.
- Shih, Y.-H., Chiu, K.-C., Wang, T.-H., Lan, W.-C., Tsai, B.-H., Wu, L.-J., Hsia, S.-M., Shieh, T.-M., 2021. Effects of melatonin to arecoline-induced reactive oxygen species production and DNA damage in oral squamous cell carcinoma. *J. Formos. Med. Assoc.* 120, 668–678.
- Sikora, E., Hajdu, V., Muránszky, G., Katona, K.K., Kocserha, I., Kanazawa, T., Fiser, B., Viskolcz, B., Vanyorek, L., 2021. Application of ion-exchange resin beads to produce magnetic adsorbents. *Chem. Pap.* 75, 1187–1195.
- Singh, A., Pal, D.B., Mohammad, A., Alhazmi, A., Haque, S., Yoon, T., Srivastava, N., Gupta, V.K., 2022. Biological remediation technologies for dyes and heavy metals in wastewater treatment: new insight. *Bioresour. Technol.* 343, 126154.
- Singh, J., Kalamdhad, A.S., 2011. Effects of heavy metals on soil, plants, human health and aquatic life. *Int. J. Res. Chem. Environ.* 1, 15–21.
- Smith, P., Adams, J., Beerling, D.J., Beringer, T., Calvin, K.V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., 2019. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. *Annu. Rev. Environ. Resour.* 44, 255–286.

- Soltani, N., Sadeghi, T., Khalili, P., Mahmoodi, M.R., Saadloo, M., Baneshi, M.R., Chermahini, S.A., Shamsizade, A., 2023. Comparing the association between heavy metals and cognitive status and depression in miners and non-miners: a study from southeast of Iran. *Neurotoxicology* 99, 97–103.
- Statwick, J., Majestic, B.J., Sher, A.A., 2016. Characterization and benefits of selenium uptake by an *Astragalus* hyperaccumulator and a non-accumulator. *Plant Soil* 404, 345–359.
- Stürmer, P., Weber, K.S., Strathmann, E.A., Lieb, W., 2024. Plasma boron concentrations and risk of all-cause mortality in the general population. *Eur. J. Nutr.* 1–7.
- Suljević, D., Sulejmanović, J., Foćak, M., Halilović, E., Pupalović, D., Hasić, A., Alijagić, A., 2021. Assessing hexavalent chromium tissue-specific accumulation patterns and induced physiological responses to probe chromium toxicity in *Coturnix japonica* quail. *Chemosphere* 266, 129005.
- Sun, Y., Niu, G., Dou, H., Perez, C., Alexander, L., 2022. Growth, gas exchange, and mineral nutrients of hydrangea hybrids irrigated with saline water. *Hortscience* 57, 319–325.
- Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K., Sutton, D.J., 2012. Heavy metal toxicity and the environment. Molecular, clinical and environmental toxicology 133–164.
- Tichy, R., 1998. Bioremediation of Metals from Soils or Sediments Using the Microbial Sulfur Cycle. Wageningen University and Research.
- Tomer, A., Singh, R., Singh, S.K., Dwivedi, S., Reddy, C.U., Keloth, M.R.A., Rachel, R., 2021. Role of fungi in bioremediation and environmental sustainability. *Mycoremediation and Environmental Sustainability* 3, 187–200.
- Tóth, G., Hermann, T., Da Silva, M., Montanarella, L., 2016. Heavy metals in agricultural soils of the European Union with implications for food safety. *Environ. Int.* 88, 299–309.
- Trujillo-Vázquez, S., Gaona-Domínguez, S., Villeda-González, J., Librado-Osorio, R., Luna-López, A., Bonilla-González, E., Valencia-Quintana, P., Gómez-Olivares, J., 2023. Oxidative stress in the ovaries of mice chronically exposed to a low lead concentration: a generational approach. *Reprod. Toxicol.* 115, 40–48.
- Tu, C., Fan, W., Yang, S., Luo, Y., 2024. Copper in the Soil. *Inorganic Contaminants and Radionuclides*, pp. 95–111.
- USEPA, 1998. Toxicological Review of Hexavalent Chromium. USEPA, Assessment, (US Environmental Protection Agency). National Center for Environment.
- van der Ent, A., Malaisse, F., Erskine, P.D., Mesjasz-Przybyłowicz, J., Przybyłowicz, W.J., Barnabas, A.D., Sośnicka, M., Harris, H.H., 2019. Abnormal concentrations of Cu–Co in *Haumaniastrum katangense*, *Haumaniastrum robertii* and *Aeolanthus biformifolius*: contamination or hyperaccumulation? *Metallomics* 11, 586–596.
- Vera, A., Moreno, J., Siles, J., López-Mondejar, R., Zhou, Y., Li, Y., García, C., Nicolás, E., Bastida, F., 2021. Interactive impacts of boron and organic amendments in plant-soil microbial relationships. *J. Hazard Mater.* 408, 124939.
- Wang, X., Liu, E., Lin, Q., Liu, L., Yuan, H., Li, Z., 2020. Occurrence, sources and health risks of toxic metal (loid) s in road dust from a mega city (Nanjing) in China. *Environ. Pollut.* 263, 114518.
- Wang, X., Yang, X., Chen, S., Li, Q., Wang, W., Hou, C., Gao, X., Wang, L., Wang, S., 2016. Zinc oxide nanoparticles affect biomass accumulation and photosynthesis in *Arabidopsis*. *Front. Plant Sci.* 6, 1243.
- Wang, Y., Mandal, A.K., Son, Y.-O., Pratheeshkumar, P., Wise, J.T., Wang, L., Zhang, Z., Shi, X., Chen, Z., 2018. Roles of ROS, Nrf2, and autophagy in cadmium-carcinogenesis and its prevention by sulforaphane. *Toxicol. Appl. Pharmacol.* 353, 23–30.
- Wang, Y., Shi, J., Wang, H., Lin, Q., Chen, X., Chen, Y., 2007. The influence of soil heavy metals pollution on soil microbial biomass, enzyme activity, and community composition near a copper smelter. *Ecotoxicol. Environ. Saf.* 67, 75–81.
- Wang, Y., Tam, N.F., 2019. Microbial Remediation of Organic Pollutants. *World Seas: An Environmental Evaluation*. Elsevier, pp. 283–303.
- Wennersten, R., Qie, S., 2018. United Nations sustainable development goals for 2030 and resource use. In: *Handbook of Sustainability Science and Research*. Springer, pp. 317–339.
- Witkowska, D., Slowik, J., Chilicka, K., 2021. Heavy metals and human health: possible exposure pathways and the competition for protein binding sites. *Molecules* 26, 6060.
- Woitke, P., Wellmitz, J., Helm, D., Kube, P., Lepom, P., Litheraty, P., 2003. Analysis and assessment of heavy metal pollution in suspended solids and sediments of the river Danube. *Chemosphere* 51, 633–642.
- Wyszkowska, J., 2002. Soil contamination by chromium and its enzymatic activity and yielding. *Pol. J. Environ. Stud.* 11, 79–84.
- Xia, Y., Tang, Y., Shih, K., Li, B., 2020. Enhanced phosphorus availability and heavy metal removal by chlorination during sewage sludge pyrolysis. *J. Hazard Mater.* 382, 121110.
- Xu, H., He, E., Peijnenburg, W.J., Song, L., Zhao, L., Xu, X., Cao, X., Qiu, H., 2021. Contribution of pristine and reduced microbial extracellular polymeric substances of different sources to Cu (II) reduction. *J. Hazard Mater.* 415, 125616.
- Yaman, E., Harmanci, P., Kaya, M.D., Kulan, E.G., 2024. Response of winter canola varieties to boron stress during germination and seedling growth stage. *Black Sea Journal of Agriculture* 7, 15–16.
- Yan, A., Wang, Y., Tan, S.N., Ghosh, S., Chen, Z., 2020a. Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. *Front. Plant Sci.* 11, 513099.
- Yan, A., Wang, Y., Tan, S.N., Mohd Yusof, M.L., Ghosh, S., Chen, Z., 2020b. Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. *Front. Plant Sci.* 11, 359.
- Yang, G., He, H., 2016. A review of pteridophyta potential in phytoremediation of heavy metal contaminated environments. *Asian Agricultural Research* 8, 49–60.
- Yang, J., Ma, Z., 2021. Research progress on the effects of nickel on hormone secretion in the endocrine axis and on target organs. *Ecotoxicol. Environ. Saf.* 213, 112034.
- Yang, L., Ren, Q., Zheng, K., Jiao, Z., Ruan, X., Wang, Y., 2022. Migration of heavy metals in the soil-grape system and potential health risk assessment. *Sci. Total Environ.* 806, 150646.
- Yang, Y., Jiang, R.-F., Wang, W., Li, H.-F., 2011. Application of rhizosphere interaction of hyperaccumulator *Nocca caerulea* to remediate cadmium-contaminated agricultural soil. *Int. J. Phytoremediation* 13, 933–945.
- Yang, Y., Wang, W., Liu, X., Song, X., Chai, L., 2020. Probing the effects of hexavalent chromium exposure on histology and fatty acid metabolism in liver of *Bufo gargarizans* tadpoles. *Chemosphere* 243, 125437.
- Yang, Z., Chen, J., Dou, R., Gao, X., Mao, C., Wang, L., 2015. Assessment of the phytotoxicity of metal oxide nanoparticles on two crop plants, maize (*Zea mays* L.) and rice (*Oryza sativa* L.). *Int. J. Environ. Res. Publ. Health* 12, 15100–15109.
- Yaqoob, A., Nasim, F., Sumreen, A., Munawar, N., Zia, M., Choudhary, M., Ashraf, M., 2019. Current scenario of phytoremediation: progresses and limitations. *Int. J. Biosci.* 14, 191–206.
- Zafar, A., Javed, S., Akram, N., Naqvi, S.A.R., 2024. Health risks of mercury. In: *Mercury Toxicity Mitigation: Sustainable Nexus Approach*. Springer, pp. 67–92.
- Zakaria, N., Gibrilla, A., Owusu-Nimo, F., Adomako, D., Anornu, G., 2022. Occurrence, spatial distribution, and health risk assessment of heavy metals in groundwater from parts of the Kassena Nankana area, Ghana. *Sustainable Water Resources Management* 8, 1–14.
- Zaynab, M., Al-Yahyai, R., Ameen, A., Sharif, Y., Ali, L., Fatima, M., Khan, K.A., Li, S., 2022. Health and environmental effects of heavy metals. *J. King Saud Univ. Sci.* 34, 101653.
- Zheng, S., Cao, X., Wang, L., Gao, X., Shen, Y., Du, J., Liu, P., Zhuang, Y., Guo, X., 2024. Insights into the effects of chronic combined chromium-nickel exposure on colon damage in mice through transcriptomic analysis and in vitro gastrointestinal digestion assay. Xianhong and Wang, luqi and gao, xiaona and shen, yufan and du, jun and liu, ping and Zhuang, yu and guo, xiaoquan, insights into the effects of chronic combined chromium-nickel exposure on colon damage. In: *Mice through Transcriptomic Analysis and in Vitro Gastrointestinal Digestion Assay*.
- Zhu, Q., Liao, S., Lu, X., Shi, S., Gong, D., Cheang, I., Zhu, X., Zhang, H., Li, X., 2021a. Cobalt exposure in relation to cardiovascular disease in the United States general population. *Environ. Sci. Pollut. Control Ser.* 28, 41834–41842.
- Zhu, T., Li, L., Duan, Q., Liu, X., Chen, M., 2021b. Progress in our understanding of plant responses to the stress of heavy metal cadmium. *Plant Signal. Behav.* 16, 1836884.
- Zuhra, N., Akhtar, T., Yasin, R., Ghafoor, I., Asad, M., Qadeer, A., Javed, S., 2024. Human health effects of chronic cadmium exposure. In: *Cadmium Toxicity Mitigation*. Springer, pp. 65–102.
- Zulfikar, U., Farooq, M., Hussain, S., Maqsood, M., Hussain, M., Ishfaq, M., Ahmad, M., Anjum, M.Z., 2019. Lead toxicity in plants: impacts and remediation. *J. Environ. Manag.* 250, 109557.