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REVIEW PAPER

Bibliometric analysis and impact of heavy metals contamination in soils

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ABSTRACT

Heavy metal contamination in soils is a critical environmental issue due to the persistent and toxic nature of these metals, which pose severe risks to ecosystems and human health. This study provides a comprehensive review of the mechanisms underlying heavy metal contamination, with a focus on key processes such as soil mineralogy, chemical forms and speciation, adsorption, precipitation, complexation, and redox reactions. These mechanisms collectively influence the mobility, bioavailability, and toxicity of heavy metals in soils. The study also employs bibliometric analysis to examine the global research trends and developments in the field of heavy metal contamination, offering insights into the evolution of scientific knowledge and highlighting emerging areas of research. In addition to exploring the fundamental processes, this study addresses the wide-ranging impacts of heavy metal contamination, including its detrimental effects on soil quality, plant growth, ecosystems, and human health. Methods for assessing soil contamination are critically reviewed, covering soil sampling protocols, advanced analytical techniques, and bioavailability assessments. These methods provide a robust framework for accurately evaluating the extent and severity of contamination. The study also discusses current challenges in addressing heavy metal contamination, such as the complexity of metal speciation, soil heterogeneity, and the potential exacerbating effects of climate change. Future directions are proposed, focusing on the development of more effective remediation strategies, strengthening regulatory frameworks, and integrating interdisciplinary approaches to ensure sustainable soil management and contamination mitigation. Through this study, the study highlights the urgent need for continued research and innovation in managing heavy metal contamination in soils. The study aims to contribute to a deeper understanding of the underlying mechanisms that control metal behavior in soils. It also seeks to inform the development of more effective strategies for soil management and remediation, ultimately contributing to the protection of ecosystems and human health.

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INTRODUCTION

Soil a critical component of terrestrial ecosystems, provide indispensable facilities such as nutrient cycling, water filtration, and habitat for microorganisms. However, its aptitude to function sustainably is progressively compromised by anthropogenic activities that introduce pollutants, among which heavy metals are a significant concern. Heavy metals, including cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), and chromium (Cr), are naturally occurring elements with significant industrial, agricultural, and technological applications. Despite their positive influence, heavy metals pose serious environmental and health risks due to their persistence, toxicity, and bioaccumulative nature (Rebello *et al.,* 2021; Pande *et al.,* 2022; Bhat *et al.,* 2022; Su *et al.,* 2023). The pollution of soils with heavy metals has emerged as a critical global concern, especially in areas experiencing fast industrialization, urbanization, and intensive agriculture. Contamination sources can be categorized into natural and artificial causes. Natural sources encompass the weathering of parent rocks and volcanic activity, which liberate metals into the soil system. Conversely, anthropogenic sources, including mining operations, industrial effluents, agricultural contributions, and inadequate waste management, markedly increase the concentration and dispersion of heavy metals in soils. Upon introduction, these metals remain stable and can endure for prolonged durations, resulting in their accumulation and subsequent environmental consequences (Srivastava *et al.,* 2017; Alengebawy *et al.,* 2021; Rashid *et al.,* 2023; Priya *et al.,* 2023). Comprehending the behaviour and destiny of heavy metals in soil systems necessitates a thorough understanding. Soils are intricate and heterogeneous systems in which heavy metals engage with diverse chemical constituents, such as minerals, organic matter, and microbial populations (Dixit *et al.,* 2015; Li *et al.,* 2022; Wan *et al.,* 2024). These interactions affect the speciation, mobility, and bioavailability of metals, therefore determining their environmental and biological impacts. Several parameters, including soil potential of hydrogen (pH), redox conditions, and the presence of competing ions, influence the mobility of heavy metals. Metals can become immobilized by adsorption onto mineral surfaces or precipitation as secondary minerals, or they may be remobilized under varying environmental circumstances, such as changes in pH or redox potential. These processes are essential for comprehending the movement of metals within the soil-water system and their potential pathways to groundwater, surface water, or the food chain (Li *et al.,* 2022; Caporale and Violante, 2016; Kicińska *et al.,* 2022; Rashid *et al.,* 2023). The environmental consequences of heavy metal pollution are significant. Heavy metals can cause soil deterioration by modifying its physical, chemical, and biological characteristics, diminishing fertility, and hindering its ability to sustain plant development. Furthermore, polluted soils serve as sources of metal pollution to nearby water bodies, exacerbating the degradation of freshwater and marine ecosystems. The effects transcend environmental concerns, directly influencing human health via soil ingestion or inhalation and indirectly through the intake of polluted food or water (Angon *et al.,* 2024; Mitra *et al.,* 2022; Rajput *et al.,* 2024). Heavy metals, like Pb and Hg, are recognized for their neurotoxic properties, while others, such as Cd, provide prolonged hazards of carcinogenesis and renal impairment (Balali-Mood *et al.,* 2021; Naija and Yalcin, 2023). Various approaches are crucial for evaluating the degree of heavy metal pollution and the associated dangers. These procedures entail the examination of the chemical species and spatial distribution of metals in soils, with the evaluation of their bioavailability and toxicity. Advanced methodologies, including sequential extraction protocols, X-ray diffraction (XRD), and inductively coupled plasma mass spectrometry (ICP-MS), permit the comprehensive evaluation of heavy metal contamination at both macroscopic and molecular scales. Alongside analytical approaches, modeling has become an essential method for predicting heavy metal behavior in soils across various environmental settings, facilitating the prediction of contamination routes and the efficacy of remediation strategies (Fernández-Martínez *et al.,* 2024; Dong *et al.,* 2023; Ambrosino *et al.,* 2023; Haghighizadeh *et al.,* 2024; Xue *et al.,* 2023). The remediation of heavy metal-contaminated soils poses considerable problems, primarily due to the intricacy of soil systems and the many processes governing metal mobility. Conventional restoration methods, like soil excavation and washing, may demonstrate inadequacy or economic impracticality at extensive sizes. Recent advancements in modeling and biochemical engineering present potential strategies

for the sustainable treatment of heavy metal pollution in soil. Phytoremediation, immobilization by chemical amendments, and electrokinetic remediation are increasingly recognized for their ability to utilize natural processes in soils to stabilize or eliminate heavy metals (Selvi *et al.,* 2019; Priya *et al.,* 2023; Sánchez-Castro *et al.,* 2023; Raffa *et al.,* 2021). This study delivers an inclusive outline of the mechanisms of heavy metal contamination in soils. It begins by exploring the sources and spatial distribution patterns of heavy metals, distinguishing between natural and anthropogenic origins. The interactions that influence the mobility and retention of metals in soils, such as adsorption, precipitation, and redox reactions, are discussed in detail, providing insights into the processes that control contamination spread and persistence. The environmental, biological, and human health impacts of heavy metal contamination are examined, highlighting the urgent need for effective monitoring and management. Furthermore, assessment methods and models used to evaluate soil contamination are reviewed, with a focus on bioavailability and toxicity assessments. Finally, the study discusses current and emerging strategies for the remediation of contaminated soils and outlines key challenges and future directions in the field. By synthesizing current knowledge on the aspects of heavy metal contamination, this study aims to contribute to a deeper understanding of the underlying mechanisms that control metal behavior in soils. It also seeks to inform the development of more effective strategies for soil management and remediation, ultimately contributing to the protection of ecosystems and human health. This study has been carried out in India, Tamil Nadu, in 2024.

Bibliometric analysis

Bibliometric analysis offers significant insights into the scientific research (Danya *et al.,* 2024) landscape of heavy metal contamination in soil, highlighting trends, prominent authors, essential journals, and prevailing themes. Soil heavy metal pollution has become a critical subject of environmental research because of its effects on human health, agriculture, and ecosystem sustainability. This section delineates significant patterns derived from bibliometric data obtained from Scopus databases utilizing keywords such as “heavy metal contamination in soil”. Over the past three decades, the volume of papers concerning heavy metal contamination in soil has consistently risen, indicating an escalating global apprehension regarding environmental degradation and sustainable agriculture methods. Between the 1990s and early 2000s, there was a progressive increase in research articles, especially concerning industrial and agricultural contamination sources, such as mining, fertilisers, and pesticides. In the past decade, the publication rate has markedly increased due to intensified interest in soil remediation technologies, risk assessment, and the effects of climate change on soil chemistry. In the same keyword search, using filters the year is selected as only 2024 to know the publication status. In the year 2024, there are 1805 documents are listed in the Scopus databased for the given keywords. A BibTeX format obtained in the Scopus search using the given query keywords is utilized in the Biblioshiny tool included in the bibliometrix package. A bibliometric analysis was performed using R studio bibliometric software (Aria and Cuccurullo, 2017) using the standard procedures. The general overview of the outcome obtained this analysis is illustrated in Fig. 1.

Some of the leading journals publishing research on heavy metal contamination in soil. The Top 5 journals include *Science of the Total Environment, Journal of Hazardous Materials*, *Environmental Science and Pollution Research*, Environmental Monitoring and Assessment and *Chemosphere* are published the 134, 74, 54, 52 and 47 documents respectively. These journals are known for high-impact publications addressing various aspects of environmental contamination, including sources, transport mechanisms, and remediation technologies. Research on heavy metal contamination is widespread, with notable contributions from nations experiencing industrialization, fast urbanization, and intensified agriculture. In that year 2024 for the given keyword search in Scopus database (Fig. 2), China, India, and Pakistan are prominent contributors to this domain such as 787, 239 and 111 documents respectively, with several research concentrating on the cleanup of contaminated sites and the health hazards associated with heavy metal exposure. The USA and the European nations, including Germany and the UK, have made substantial contributions, especially in formulating legal frameworks for soil contamination. Leading institutions in this research area include the Chinese Academy of Sciences, Ministry of Education

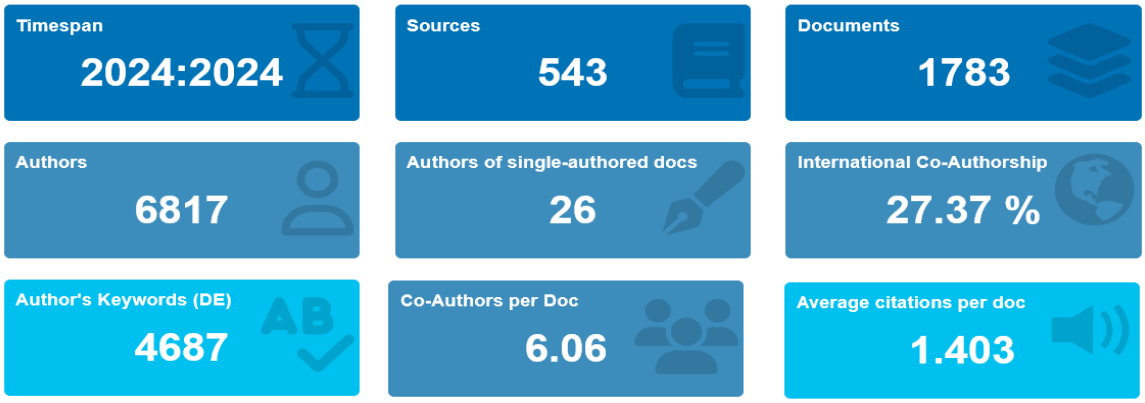


Fig. 1: General overview of key information for the retrieved document search in the Scopus database

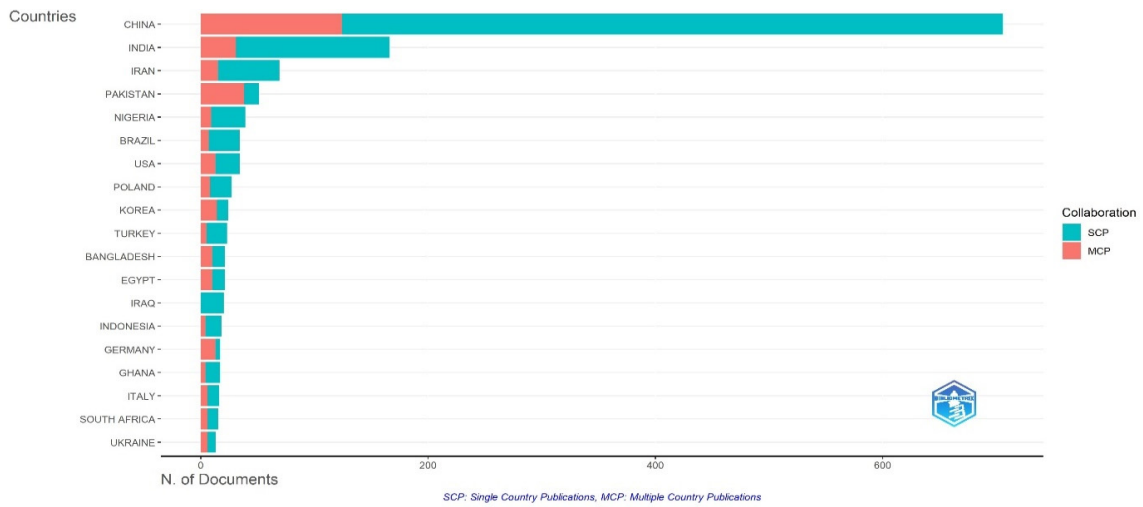


Fig. 2: Corresponding author countries for the retrieved document list

of the People's Republic of China, and King Saud University are published 124, 113 and 61 documents which are listed in the Scopus database. It is being observed that National Natural Science Foundation of China, Ministry of Science and Technology of the People's Republic of China, and National Key Research and Development Program of China are the Top 3 funding agency for the 377, 291, and 146 documents respectively.

Some of the most prolific authors in the field include scientists specializing in soil chemistry, environmental toxicology, and ecological restoration. Researchers such as Wang, Y., Zhang, Y., Li, J. from China have contributed substantially to the literature on heavy metal dynamics in soils, remediation strategies, and the impacts of contamination on agricultural productivity. The three-field plot (Fig. 3) created using Biblioshiny shows a relationship between the authors and countries with the highest scientific production and the major journal sources related to heavy metal contamination in soil and the connected keywords.

A co-occurrence analysis identifies multiple subject groups in the literature. In Fig. 4, the predominant cluster is to the evaluation and surveillance of heavy metal concentrations in soils, especially concerning agricultural land and urban settings. A notable cluster emphasizes remediation approaches, such as phytoremediation, bioremediation, and soil

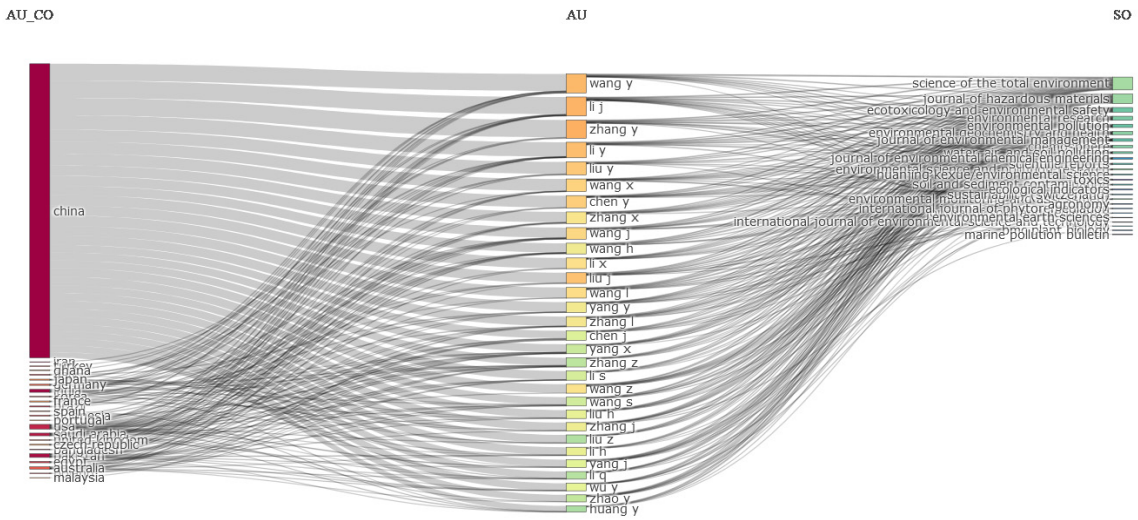


Fig. 3: Three-field plot for the selective keywords

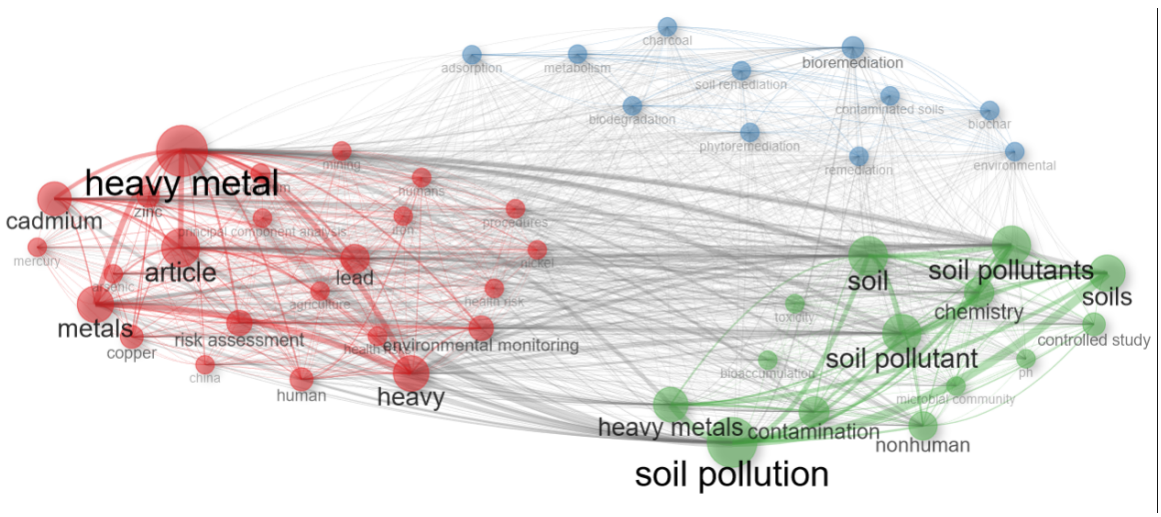
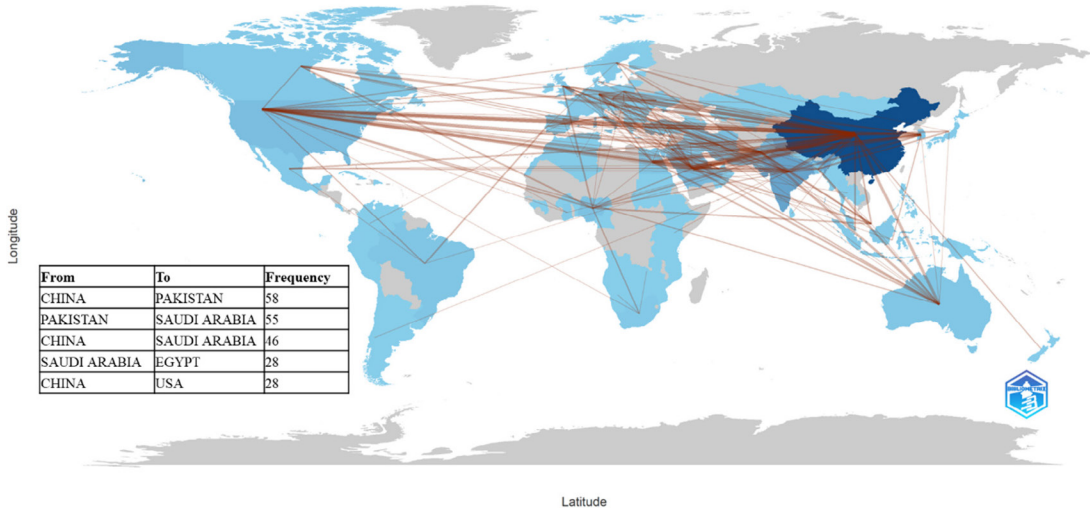


Fig. 4: Co-occurrence network generated for the author keywords for the documents

washing technologies. Contemporary research trends have transitioned to investigating the application of nanotechnology in soil remediation and the interplay between heavy metals and organic contaminants, underscoring the interdisciplinary character of the domain. Current issues encompass the investigation of bioavailability and toxicity mechanisms of heavy metals within the framework of climate change, as well as the function of soil microbial communities in alleviating contamination.

Investigations into heavy metal contamination in soil are characterized by extensive collaboration, with several multinational partnerships forming to tackle this global environmental issue. Heavy metal contamination crosses national borders, being strongly associated with industrial activity, agricultural practices, and regional environmental legislation. The examination of international cooperation (Fig. 5) indicates substantial relationships between established and developing countries, each



From	To	Frequency
CHINA	PAKISTAN	58
PAKISTAN	SAUDI ARABIA	55
CHINA	SAUDI ARABIA	46
SAUDI ARABIA	EGYPT	28
CHINA	USA	28

Fig. 5: Countries collaboration map: This map created for the documents published in the year 2024

offering specialised knowledge in several areas of soil contamination, including detection, monitoring, remediation technologies, and policy formulation. Top 3 collaboration for the published documents for the given keyword search in Scopus database showed between China-Pakistan, Pakistan-Saudi Arabia, and China-Saudi Arabia in the year 2024.

Bibliometric analysis underscores the dynamic expansion and interdisciplinary character of research concerning heavy metal contamination in soils. The subject has transitioned from solely environmental issues to include wider concerns on human health, sustainable agriculture, and technical advancements in remediation. As focus intensifies on sustainable development goals, especially with environmental sustainability and food security, research on soil contamination by heavy metals is expected to proliferate, fostering greater multidisciplinary collaboration in the future. This bibliometric analysis presents an overview of the current state of the topic, providing essential insights for researchers seeking to discern trends, find possible collaborators, and recognize gaps in the literature that require additional investigation (Fig. 5). In conclusion, by analyzing research trends, influential publications, and citation networks, it can reveal the most studied contamination sources (e.g., industrial activities, agriculture) and pathways (e.g., runoff, atmospheric deposition). By identifying relevant research on biological impacts, bibliometric analysis can deepen understanding of how heavy metals affect soil microbial communities and plant health. Bibliometric analysis highlights research gaps, showing areas with limited studies or inconsistent findings. By identifying under-researched topics, such as less-studied metals or regional disparities in research, it can direct future studies to fill these gaps and advance understanding of soil contamination dynamics. This analysis also identifies key researchers, institutions, and collaborations in the field.

Impacts of heavy metals contamination

Heavy metal contamination is now a major global environmental and public health concern, as its widespread presence in soil, water, and air poses serious threats to living organisms. Metals like Pb, Cd, Hg, As, and Cr are non-biodegradable and accumulate in biological systems, leading to long-lasting harmful effects. While these metals naturally enter the environment through processes like volcanic activity and erosion, human activities—including industrial operations, mining, agriculture, and improper waste management—have significantly accelerated their spread. Once heavy metals are introduced into the soil, they interfere with natural soil processes, affecting microbial ecosystems, diminishing soil

fertility, and hindering plant growth. These metals can also infiltrate the food chain through crops cultivated in contaminated soils, resulting in bioaccumulation and presenting serious risks to human and animal health. Prolonged exposure to heavy metals has been associated with various health problems, including neurotoxicity, cancer, kidney damage, and developmental abnormalities (Kumari *et al.,* 2021; Alengebawy *et al.,* 2021; Angon *et al.,* 2024). Metal pollution represents a critical environmental issue that negatively impacts ecosystems, affecting plants, animals, and humans alike. Certain metals, even at low concentrations, can be highly toxic due to their non-recyclable nature. Metals are categorized into three groups: the first group includes highly toxic elements such as Hg, Pb, and Cd; the second encompasses less toxic metals like thallium (Ti), bismuth (Bi), and As; and the third consists of essential metals, including zinc (Zn), Cu, Fe, and cobalt (Co), which can be harmful at specific concentrations and play vital roles in various biochemical processes within the body. These toxic metals can accumulate in soil and biological tissues through multiple exposure pathways, including the inhalation of polluted air (Briffa *et al.,* 2020; Raj *et al.,* 2023; Mitra *et al.,* 2022).

Environmental impacts, soil degradation and water contamination

Pb contamination in the environment arises from various anthropogenic sources, including mining, waste from battery and metal plating industries, smelters, and the use of agricultural fertilizers and pesticides. Industries such as those in newspapers, pharmaceuticals, food and beverage production, and pulp preservation discharge considerable amounts of toxic metals into the environment. Notably, coal mineral fertilizers often contain elevated levels of heavy metals like Cd and Pb (Raj *et al.,* 2023). The availability of lead in soil is primarily absorbed by plants, with its mobility and solubility influenced by specific biochemical factors, including potential of hydrogen (pH), microbial conditions, and plant species (Mohanty *et al.,* 2017). The permissible limit for Pb in the environment is typically set between 0.10 and 0.30 microgram per cubic meters (µg/m^3); however, during winter months, air pollution levels in India have been reported at 1 µg/m^3, significantly exceeding this threshold. The absorption of metals in soil and plants is modulated by biological and other factors, with soil pH playing a pivotal role in lead availability. In acidic soils (pH < 6), lead is predominantly present in an aqueous form, while in alkaline soils (pH > 7), it forms complexes with hydroxide ions. Lead can be biomagnified through food chains, posing serious threats to living organisms (Nyiramigisha *et al.,* 2021). Pb contamination in soil has been associated with significant disruptions in the metabolic functions of organisms. Additionally, lead pollution contributes to deficiencies in essential soil macronutrients, such as phosphorus, which further exacerbates nutrient imbalances (Fenn *et al.,* 2006). The presence of lead also inhibits soil enzyme activities, resulting in reduced levels of critical enzymes including urease, catalase, invertase, and acid phosphatase. These enzyme disruptions further compromise soil health. Lead interferes with water balance, enzyme activities, and mineral nutrition, leading to diminished soil productivity and overall environmental degradation (Golia *et al.,* 2023; Nyiramigisha *et al.,* 2021). Cd contamination in soil has been shown to cause significant metabolic dysfunctions in organisms. Additionally, Cd adversely affects critical soil enzymes, inhibiting the activities of protease, urease, and alkaline phosphatase. This enzymatic disruption not only impairs soil health but also reduces the availability of essential nutrients such as nitrogen (N) and sulfur (S), which are vital for crop production, thereby negatively influencing agricultural productivity (Golia, 2023). Zn contamination in soil is known to be phytotoxic, significantly affecting soil fertility. Excessive Zn levels can reduce microbial biomass N, a key component in maintaining soil nutrient balance. Furthermore, Zn toxicity can lead to deficiencies in essential macronutrients, particularly phosphorus (P), further compromising soil health and fertility (Fenn *et al.,* 2006; Briffa *et al.,* 2020; Ahmed *et al.,* 2020). Cu contamination in soil has been shown to reduce the availability of essential nutrients such as N and S, which are critical for crop production. Additionally, Cu inhibits the activity of β-glycosidase to a greater extent than that of cellulose (Golia, 2023). This inhibition further contributes to a decrease in microbial biomass N, impacting overall soil health and nutrient cycling (Yao *et al.,* 2003; Ahmed *et al.,* 2020). Hg contamination in soil is linked to considerable disruptions in the metabolic functions of organisms. These abnormalities can result in a range of negative

consequences for soil health and overall ecosystem stability (Nyiramigisha *et al.,* 2021).

Biological effects on soil microorganisms and plants

Heavy metal contamination poses significant disruptions to vital soil microbial processes, including nutrient cycling and organic matter decomposition, which are crucial for maintaining soil health. Toxic metals such as Cd, Pb, Hg, and As adversely affect microbial cell structures, enzymes, and genetic material, resulting in decreased microbial activity and diversity. Elevated metal concentrations particularly diminish populations of sensitive microbial species, thereby impairing key ecological functions like nitrogen fixation. While certain microbes develop resistance mechanisms, such as efflux pumps and metal sequestration, these adaptations often come with a metabolic trade-off, reducing their functional efficiency. Furthermore, heavy metals inhibit essential soil enzymes, including dehydrogenases and phosphatases, leading to a decline in organic matter decomposition and nutrient transformation, which ultimately lowers soil fertility (Angon *et al.,* 2024; Pande *et al.,* 2022). It is estimated that the effect of all the enzymes in the soil were significantly reduced to 10-50 times, with the increase in heavy metal concentrations (Su *et al.,* 2014). Low concentration of heavy metals does not hinder with plant growth, when the concentrations increase above the threshold limit, it might cause some adverse effects on plants. The concentration of copper greater than 50 milligrams per kilogram (mg/kg) will affect citrus seedlings, while if its concentration reaches 200 mg/kg, it will make wheat crops to wither (Adrees *et al.,* 2015; Hippler *et al.,* 2018). Cd toxicity has profound inhibitory effects on plant germination and growth, significantly reducing agricultural productivity. Exposure to toxic Cd levels disrupts seedling physiology and suppresses germination, as observed in multiple crops (Guilherme *et al.,* 2015). Studies have shown that Cd at a concentration of 5 milligrams per liter (mg/L) can reduce germination in crops like soybean, lettuce, and sugar beet by 8 percent (%), 19%, and 18%, respectively (Guilherme *et al.,* 2015), highlighting the widespread impact of Cd on seedling establishment. In cowpea (*Vigna unguiculata* L.), Cd-induced inhibition is primarily due to decreased water absorption, which limits the water supply necessary for embryo development (Vijayaragavan *et al.,* 2011). Prolonged Cd exposure leads to root necrosis, decomposition, and the formation of mucilaginous tissues, significantly restricting root and shoot elongation while inducing symptoms such as leaf rolling and chlorosis (Abbas *et al.,* 2017). Stress induced by Cd results in visible symptoms in plant leaves, including chlorosis, stunting, desiccation, and necrosis, particularly when Cd concentrations in plant tissues surpass 3–30 mg/kg (Ismael *et al.,* 2018). High Cd levels are known to inhibit cellular and overall plant growth in crops such as chickpea, lentil, alfalfa, wheat, maize, spinach, and soybean (Abbas *et al.,* 2017; Zhang *et al.,* 2019). Cd exposure has been shown to significantly reduce the uptake of elements like P, potassium (K), S, calcium (Ca), and Zn in species such as sugar beet, pea, and barley (Guo *et al.,* 2007). Additionally, Cd toxicity accelerates the production of reactive oxygen species (ROS), damaging the photosynthetic machinery, particularly the light-harvesting complexes and photosystems I and II (Haider *et al.,* 2021). Cd-induced iron deficiency further disrupts photosynthesis by impairing chlorophyll synthesis and pigment production necessary for light absorption. Such disruptions have been observed across several crops, including rapeseed, alpine pennygrass, pea, maize, barley, mungbean, and wheat, where Cd exposure inhibits photosynthetic efficiency (Popova *et al.,* 2012; Abbas *et al.,* 2017).

Human health risks and exposure pathways

Majority of heavy metals are present in the environment such as rocks, soils and water and some are released into the environment via anthropogenic activities such as mining and Industrial activities, pose health hazards to humans upon exposure. Most common heavy metals from Industrial process are antimony (Sb), AS, Cd, Cr, Hg, Cu, Pb, Zn and Ti. Heavy metals enter into our body by various means such as oral route, breathing, skin exposure, etc., of which oral route was the most common means of ingestion of heavy metals. Excessive exposure to these heavy metals affects the internal organs and pose respiratory disorders, carcinogenicity, neurological effects, alimentary canal defects, osteoporosis, etc. (Mithra *et al.,* 2021). Essential minerals like Cu, Cr, Fe, Mn, and Zn, at specific concentrations are vital for metabolic and biological functions in animals and humans. In contrast, elements such as As, Cd, Pb, and

Hg are non-essential and highly toxic, offering no nutritional or biological benefits (Khan *et al.,* 2015). Municipal solid waste incinerators emit harmful elements like Pb, Cr, Cd, and Mn into the air and water, which can enter the body through inhalation and skin contact and cause respiratory disorders and allergic responses (Li Tong *et al.,* 2017). Cd exposure in humans occurs primarily via inhalation in industrial environments, such as metal smelting and battery manufacturing, and through dietary intake, particularly from crops cultivated in contaminated soils. The respiratory system absorbs 30% to 50% of Cd in occupational settings (Elinder, 2019). Additionally, environmental sources like microplastics from car tires and smoking in confined spaces contribute to Cd contamination. For the general population, food remains the predominant source of Cd exposure, notably from seafood and shellfish (Qu *et al.,* 2024). Cadmium primarily targets the liver and renal cortex. Upon ingestion, it accumulates in the liver, contributing to multiple dysfunctions, including hepatocellular damage and oxidative stress. These effects can progressively lead to liver failure and heighten the risk of carcinogenesis (Hyder *et al.,* 2013). In the kidneys, Cd affects the proximal tubular epithelium, causing elevated levels of Cd in urine. Prolonged exposure can result in renal tubular acidosis, renal failure, and hypercalciuria (Friberg *et al.,* 2019). Other clinical manifestations of Cd exposure include diabetes, hypertension, stroke, myocardial infarction, carotid atherosclerosis, peripheral artery disease and heart failure (Mitra *et al.,* 2022). Hg, a highly toxic heavy metal, is transformed into methylmercury upon contact with aquatic sediments. Methylmercury enters the human body through the food chain, primarily via the consumption of contaminated fish, seafood, and wildlife. Once ingested, it permeates the body and induces a range of neurological disorders (Rice *et al.,* 2014). Additionally, Hg generates significant quantities of reactive oxygen species (ROS), which promote the proliferation of cancerous cells (Zefferino *et al.,* 2017). Hg exposure also affects renal function, leading to acute tubular necrosis, and chronic exposure can result in Hg-induced chronic kidney injury (Lentini *et al.,* 2017). Pb a non-biodegradable metal, are released into atmosphere through anthropogenic activities such as production process, mining, and combustion of fossil fuels. This rise in lead levels poses significant health risks, especially in children, where exposure can lead to severe lead poisoning through contact with contaminated dust (Loh *et al.,* 2016). Pb's toxicity predominantly affects the kidneys, leading to both acute and chronic nephropathies, including tubular dysfunction, fibrosis, and eventually renal failure. It is also carcinogenic, as it impairs Deoxyribonucleic acid (DNA) repair mechanisms and disrupts cellular functions by generating reactive oxygen species. Furthermore, Pb compromises the immune system, increasing the likelihood of allergies, infections, autoimmune diseases, and cancers such as lung, stomach, and bladder cancer (Hsiao *et al.,* 2011). Additionally, chronic exposure to Pb has been linked to cardiovascular diseases, such as arteriosclerosis, hypertension, and heart disease, primarily due to oxidative stress, inflammation, and vascular dysfunction (Vaziri, 2008). Ti, an extremely toxic metal compared to other heavy metals, present in various environmental forms. Natural water contains monovalent Ti ions are released into the atmosphere through aqueous pathways. Industrial activities significantly contribute to elevated Ti levels in the air, and exposure to this metal is highly detrimental to human health (Kazantzis, 2000). The excretion of thallium sulfate by the kidneys is notably slow, taking up to two months after ingestion, which can lead to toxic kidney damage manifesting as albuminuria and hematuria, although it generally does not severely impair renal function (Yumoto *et al.,* 2017). Studies of thallium poisoning in animals and humans show that it causes substantial damage to the brain and peripheral nerves, including cerebral edema, vascular engorgement, altered brain capillaries, cerebellar edema with pyknotic Purkinje cells, and localized necrosis (Mithra *et al.,* 2021). Impact of heavy metals on Crops/ Plants and Humans are listed in Table 1. Mn, one of the most prevalent toxic heavy metals, is released into the atmosphere as manganese oxides during the combustion of methylcyclopentadienyl manganese tricarbonyl (MMT), a gasoline additive. Although Mn is vital for several physiological functions, chronic high-level exposure is associated with severe neurological conditions such as Alzheimer's and Parkinson's diseases, which can cause cell death and disrupt homeostasis (Goldhaber, 2003). The regulation of Mn levels within cells involves mechanisms for intake, storage, and

Table 1: Impact of heavy metals

Heavy metals	Influence on crop viability and soil microbes	Sources	Exposure pathway to humans	Target organs	Health impacts	Sources
Cd	Limit the availability of nitrogen and sulfur in the soil for crop cultivation.	Akanchise *et al.*, 2020	Smoking, Inhalation, Dietary intake through contaminated food and water.	Liver	Leads to hepatocellular damage, oxidative stress, Liver failure and can lead to cancer	Hyder *et al.*, 2013
	Hinders the metabolic process of Microbes	Bakshi *et al.*, 2018		Kidney	affects proximal convoluted tubule, causes elevated levels of cadmium in urine	Friberg *et al.*, 2019
	Disrupt the activity of protease, urease and alkaline phosphatase in soil.	Bakshi *et al.*, 2018 Karaca *et al.*, 2010			Prolonged exposure - renal tubular acidosis, renal failure, and hypercalciuria.	Friberg *et al.*, 2019
	May have negative effects on sugar content and amino acids in certain plant species by increasing their concentration, suggesting an inhibition of starch hydrolysis.	Singh *et al.*, 2020			Other clinical manifestations include diabetes, hypertension, stroke, myocardial infarction, carotid atherosclerosis, peripheral artery disease and heart failure	Mitra *et al.*, 2022
	Contaminating the soil disrupts phytochelatin production by blocking transporters or channels responsible for loading other elements, leading to an imbalance in plant nutrients.	Bakshi *et al.*, 2018				
Cu	Decreased the availability of soil nitrogen and sulfur for crop growth. Inhibited β-glycosidase activity to a greater extent than cellulase activity.	Bakshi *et al.*, 2018 Karaca *et al.*, 2010	Inhalation, Air, food and water, A little extent in dermal route	Liver	Excess copper builds up in the body - Wilson's disease, Indian childhood cirrhosis, and idiopathic copper toxicosis	Mithra *et al.*, 2021
	Reduces the nitrogen content of Microbial biomass	Yao *et al.*, 2003				
	Decreased the availability of soil nitrogen and sulfur for crop cultivation.	Bakshi *et al.*, 2018				
Pb	• Impairs soil enzyme activities by reducing urease, catalase, invertase, and acid phosphatase activity. • Disrupts water balance, enzyme function, and mineral nutrition.	Bakshi *et al.*, 2018 Karaca *et al.*, 2010	Inhalation, Ingestion of contaminated food and water and Dermal route	Kidney	Cause acute and chronic nephropathies, including tubular dysfunction, fibrosis, and eventually renal failure	Hsiao *et al.*, 2011
	Lowers soil productivity	Bakshi *et al.*, 2018			Compromise immune system - leads to allergy, autoimmune diseases, increased risk of lung, stomach and bladder cancer	Hsiao *et al.*, 2011
	Deficiency of soil macronutrients, such as phosphorus.	Fenn *et al.*, 2006			Other clinical manifestations include cardiovascular diseases, such as arteriosclerosis, hypertension, and heart disease, primarily due to oxidative stress, inflammation, and vascular dysfunction	Vaziri, 2008
	Slow down seed germination process	Singh *et al.*, 2020				
	Hinders plant growth, reduced chlorophyll biosynthesis, hormonal imbalances, and increased production of reactive oxygen species (ROS), ultimately resulting in metabolic dysfunction.	Tang *et al.*, 2017				

Table 1: Impact of heavy metals

Heavy metals	Influence on crop viability and soil microbes	Sources	Exposure pathway to humans	Target organs	Health impacts	Sources
Hg	Irregularities in the metabolic functions of organisms.	Akanchise *et al.*, 2020	Inhalation, Ingestion or dermal contact	Kidney	acute tubular necrosis, mercury-induced chronic kidney injury	Lentini *et al.*, 2017
				Nervous system	Neurological defects	Rice *et al.*, 2014
Zn	Reduce microbial biomass nitrogen. Deficiency of soil macronutrients, such as phosphorus. Phytotoxic and can directly impact crop yield.	Fenn *et al.*, 2006 Yao et al., 2003 Balkhair and Ashraf, 2016	Inhalation, Ingestion or dermal contact		Clinical Manifestations include acute kidney injury, pancreatic injury, liver failure, and hemodynamic instability	Agnew, 2022
Cr	Slow down or halt the growth of plants Disturb the absorption pattern of various essential minerals such as Calcium and Magnesium	Zaheer *et al.*, 2015 Zulfiqar *et al.*, 2023	Inhalation, Ingestion or dermal contact	Immune System	Type I and delayed type (Type IV) Hypersensitivity	Mithra *et al.*, 2021
Ti	Alters the soil pH to acidic range Decreases microbial community in soil	She *et al.*, 2022	Inhalation, Ingestion or dermal contact	Kidney	Can lead to toxic kidney damage such as albuminuria and hematuria	Yumoto *et al.*, 2017
				Brain and Peripheral Nerves	cerebral edema, vascular engorgement, altered brain capillaries, cerebellar edema with pyknotic Purkinje cells, and localized necrosis	Mithra *et al.*, 2021
Mn	Decrease in plant biomass	Li *et al.*, 2021	Inhalation, Ingestion or dermal contact	Brain	Alzheimer's and Parkinson's diseases	Goldhaber, 2003
As	Disrupts metabolic processes and hampers plant growth and development due to arsenic-induced phytotoxicity.	Shrivastava *et al.*, 2015	Inhalation. Ingestion, Little extent on dermal contact	Kidney	Chronic renal insufficiency from cortical necrosis	Shrivastava *et al.*, 2015
				Reproductive system	Endometriosis, reduced fertility, premature births, and spontaneous abortions	Milton *et al.*, 2017

excretion. Under conditions of excessive Mn exposure, the receptors responsible for its uptake are down-regulated, while those involved in its excretion are up-regulated. Persistent Mn accumulation can lead to increased ROS formation, contributing to mitochondrial dysfunction and ultimately leading to apoptosis (Harischandra *et al.,* 2019). Chronic exposure to As can lead to various skin conditions, such as hyperkeratosis, hyperpigmentation, and different types of skin cancer, with hyperpigmentation being the most common outcome. As can also induce Bowen's disease, an early stage of skin cancer, and cause hyperkeratosis on areas like the soles and palms, as well as other body parts. Some of these lesions may progress to invasive cancers (Huang *et al.,* 2019). In experimental animals, As exposure results in neural tube defects and negatively impacts male reproductive health by reducing sperm count, and altering testosterone and gonadotropin levels (Kim and Kim, 2015). For females, As exposure is associated with an increased risk of endometrial cancer and impairs endometrial angiogenesis essential for embryo development, leading to complications such as endometriosis, reduced fertility, premature births, and spontaneous abortions (Milton *et al.,* 2017). In general, the hazardous effects pose by heavy metals outweighs its benefits. Over exposure of Sb leads to cancer. Chromium has found to have deleterious effects on immune system. Studies has found that exposure to chromium provokes allergic contact dermatitis, also Type I and IV hypersensitivity reactions (Mithra *et al.,* 2021). Although present in trace amounts, antimony pose several health hazards and its concentration increases during volcanic eruptions and anthropogenic activities. Prolonged exposure, particularly among industrial workers through inhalation, can lead to Sb toxicity, resulting in conditions such as pancreatitis, cardiotoxicity, and various respiratory issues, including pleural adhesions, emphysema, bronchitis, respiratory irritation, and inactive tuberculosis. Additionally, SB is carcinogenic and poses risks to reproductive health (Sundar and Chakravarty, 2010).

Processes and assessment techniques for heavy metal contamination in soils

Understanding the mechanisms behind heavy metal contamination is essential for predicting metal mobility, bioavailability, and potential environmental impacts. Several key processes govern the behavior of heavy metals in soils, which are influenced by soil mineralogy, chemical speciation, adsorption, precipitation, complexation, and redox reactions. Each of these aspects plays a crucial role in determining how metals are retained or released within soil environments (Li *et al.,* 2022; Wan *et al.,* 2024; Ahmed *et al.,* 2022; Justus Reymond and Sudalaimuthu, 2023). Soil mineralogy significantly influences the retention and mobility of heavy metals. Clay minerals, oxides, and organic matter in soils provide sites for metal retention through adsorption, ion exchange, and incorporation into mineral lattices. For example, clays like montmorillonite and kaolinite have high cation exchange capacities, which help bind metals such as Cd, Pb, and Copper (Cu). Soil organic matter also plays a crucial role in metal retention through the formation of organo-metallic complexes, reducing metal mobility. Understanding the mineralogical composition of soils is thus critical for predicting the fate of heavy metals (Chu *et al.,* 2022; Sathish *et al.,* 2024; Govarthanan *et al.,* 2024; Palanisamy, 2024). The chemical forms, or speciation, of heavy metals in soils determine their solubility, mobility, and toxicity. Metals can exist in various forms, including free ions, precipitated minerals, adsorbed species, or complexes with organic and inorganic ligands. Speciation is influenced by pH, redox potential, and the presence of competing ions. For instance, under acidic conditions, metals such as Pb and Zn tend to become more soluble, increasing their mobility and bioavailability. Speciation analysis using techniques like X-ray absorption spectroscopy (XAS) and ICP-MS is critical for understanding the environmental behavior of heavy metals (Caporale and Violante, 2016; Alengebawy *et al.,* 2021; Mitaphonna *et al.,* 2024; Kicińska *et al.,* 2022). Adsorption is one of the primary processes that control the retention of heavy metals in soils. Metals can be adsorbed onto mineral surfaces, such as clay particles and oxides, via ion exchange or surface complexation. Precipitation occurs when metals react with soil components to form insoluble compounds, such as carbonates, hydroxides, and sulfides, reducing their mobility. Complexation with organic matter or inorganic anions also affects metal behavior by stabilizing metals in solution or enhancing their mobility. The balance between these processes depends on environmental factors, such as pH, ionic

strength, and the availability of binding sites (Mnasri-Ghnimi and Frini-Srasra, 2019; Yu *et al.,* 2023; Campillo-Cora *et al.,* 2020). Redox reactions play a pivotal role in controlling the mobility and speciation of heavy metals in soils. Changes in redox potential, often driven by microbial activity or environmental factors like flooding, can alter the valence state of metals, thereby influencing their solubility and toxicity. For example, under reducing conditions, metals like Cr and As may undergo reduction, leading to the formation of more mobile and toxic species (e.g., Cr(III) to Cr(VI) or As(III) to As(V)). Conversely, in oxidizing environments, metals such as iron (Fe) and manganese (Mn) may precipitate as oxides, sequestering heavy metals. Understanding these redox dynamics is crucial for predicting the environmental behavior of heavy metals in diverse soil systems (Biswas *et al.,* 2018; Meng *et al.,* 2019; Xu *et al.,* 2022; Sarkar *et al.,* 2021). Accurately assessing heavy metal contamination in soils requires the application of rigorous methods. These methods enable the identification, quantification, and evaluation of contamination levels, and offer insights into the bioavailability and toxicity of metals. The two key components of this process are soil sampling and analytical techniques, as well as bioavailability and toxicity assessments. Together, they provide a comprehensive understanding of contamination levels and their potential ecological and health impacts (Haghighizadeh *et al.,* 2024; Jiang *et al.,* 2020; Dange *et al.,* 2024; Saleem *et al.,* 2024). Soil sampling is the first critical step in assessing heavy metal contamination. It involves the collection of representative soil samples that reflect the heterogeneity of the study area. The design of a sampling program depends on factors such as the purpose of the study, land use patterns, historical contamination, and the type of metals being investigated. Proper sampling protocols must be followed to avoid cross-contamination and ensure accurate results (Chen *et al.,* 2022; El Behairy *et al.,* 2022; Zhao *et al.,* 2022; Świdwa-Urbańska and Batlle-Sales, 2021). Once samples are collected, they are subjected to a range of analytical techniques to quantify the concentration of heavy metals. ICP-MS is one of the most sensitive methods for detecting trace levels of heavy metals in soils. It can measure a wide range of elements simultaneously and is widely used due to its high precision and accuracy. X-ray fluorescence (XRF) is a non-destructive technique used for the rapid screening of heavy metals in soil. It provides semi-quantitative to quantitative results, making it a valuable tool for initial contamination assessment. Sequential extraction procedures (SEP) help to determine the fractionation of metals within the soil, identifying which metals are bound to specific soil components. SEP gives insight into the bioavailability and potential mobility of metals under varying environmental conditions. Each of these techniques offers distinct advantages, and their combination can provide a more complete picture of heavy metal contamination in soils (Wilschefski and Baxter, 2019; Marguí *et al.,* 2022; Al Maliki *et al.,* 2017; Croffie *et al.,* 2020). While total metal concentrations are important, they do not provide a full understanding of the environmental risks posed by heavy metals. Metal bioavailability, which refers to the fraction of the total metal content that is available for uptake by organisms, is critical for assessing the ecological and health impacts of soil contamination. Chemical Extraction Methods involve the use of selective extractants to simulate environmental conditions that could release metals from the soil matrix. Commonly used extractants include Ethylenediaminetetraacetic acid (EDTA) and ammonium nitrate (NH_4NO_3) (Cipullo *et al.,* 2018; Wieczorek *et al.,* 2023; Zhu *et al.,* 2023). In-vitro bioaccessibility tests (IVBA) simulate gastrointestinal conditions to estimate the fraction of metals that could be absorbed into the human body if contaminated soil is ingested. IVBA is particularly important for assessing the risks to children from ingesting contaminated soil through hand-to-mouth contact (Li *et al.,* 2020; Griggs *et al.,* 2022; Fang *et al.,* 2022). Plant-based studies help determine the extent to which plants absorb heavy metals from contaminated soils. These studies are vital for assessing the potential entry of metals into the food chain and for identifying plants that can be used in phytoremediation (Priya *et al.,* 2023; Bhat *et al.,* 2022). Toxicity characteristic leaching procedure (TCLP) simulates leaching processes that occur in landfills, helping to determine whether heavy metals in the soil could contaminate groundwater under landfill conditions. Toxicity assessments involve both ecotoxicological and human health risk evaluations (Intrakamhaeng *et al.,* 2019; Ghazali *et al.,* 2022). Ecotoxicological studies typically focus on how metals

Table 2: Key processes and assessment techniques for heavy metal contamination in soils

Process	Description	Associated heavy metals	Key techniques	Sources
Soil mineralogy	Determines metal retention through adsorption, ion exchange, and lattice incorporation	Cd, Pb, Cu, Zn	X-ray diffraction (XRD), scanning Electron Microscopy (SEM)	Chu *et al.,* 2022; Govarthanan *et al.,* 2024
Chemical speciation	Defines metal solubility, mobility, and toxicity based on chemical forms (free ions, adsorbed species, etc.)	Pb, Zn, As	X-ray absorption spectroscopy (XAS), ICP-MS, sequential Extraction Procedure (SEP)	Caporale and Violante, 2016; Kicińska *et al.,* 2022
Adsorption	Metals adhere to mineral surfaces, reducing mobility through ion exchange and complexation	Cu, Cd, Pb	Batch adsorption tests, Fourier Transform Infrared Spectroscopy (FTIR)	Mnasri-Ghnimi and Frini-Srasra, 2019; Yu *et al.,* 2023
Precipitation	Formation of insoluble metal compounds (e.g., sulfides, hydroxides) reducing bioavailability	Cr, Mn, Pb	Scanning Electron Microscopy (SEM), XRD	Biswas *et al.,* 2018; Meng *et al.,* 2019
Complexation	Metals form stable complexes with organic or inorganic ligands, affecting solubility	Cu, Cd, As	Complexometric titration, Spectroscopy-based techniques	Mnasri-Ghnimi and Frini-Srasra, 2019
Redox reactions	Alters metal valence states, impacting mobility and toxicity under oxidizing/reducing conditions	Cr, As, Fe	Redox potential measurements, Electrochemical analysis	Biswas *et al.,* 2018; Xu *et al.,* 2022
Soil sampling	Collection of representative samples for metal contamination assessment	All heavy metals	Stratified sampling, Core sampling	Chen *et al.,* 2022; Świdwa-Urbańska and Batlle-Sales, 2021
Analytical techniques	Measurement of metal concentration and distribution in soils	Cd, Pb, Hg, As	ICP-MS, X-ray fluorescence (XRF), atomic absorption spectroscopy (AAS)	Wilschefski and Baxter, 2019; Marguí *et al.,* 2022
Bioavailability assessments	Determines the fraction of metal available for biological uptake	Cd, Pb, Zn	In-vitro bioaccessibility tests (IVBA), chemical extraction (EDTA, NH_4NO_3)	Fang *et al.,* 2022; Griggs *et al.,* 2022
Toxicity characteristic leaching procedure (TCLP)	Simulates landfill conditions to assess potential groundwater contamination	Pb, Cd, Hg	TCLP leaching tests	Intrakamhaeng *et al.,* 2019; Ghazali *et al.,* 2022

affect soil microbial communities, plant growth, and invertebrate organisms. Meanwhile, human health risk assessments estimate the potential for adverse effects based on exposure pathways such as direct soil ingestion, dermal contact, and inhalation of dust (Rai *et al.,* 2019; Okereafor *et al.,* 2020; Hlihor *et al.,* 2022). Integrating bioavailability assessments with total concentration measurements is essential for determining the real risks posed by heavy metal contamination. This approach ensures that remediation efforts target the most hazardous fractions of metals and offers a more realistic estimate of the environmental and health risks associated with contaminated soils (Alengebawy *et al.,* 2021). Table 2 exhibits the key Processes of heavy metals and their assessment Techniques.

Challenges and future directions

Complex Metal Speciation and Environmental Behavior: One significant challenge lies in the complexity of metal speciation, as heavy metals exist in multiple chemical forms with varying mobility, bioavailability, and toxicity (Caporale and Violante, 2016; Kicińska et al., 2022). The dynamic interactions among factors such as pH, organic matter content, and redox conditions complicate predictions of metal behavior in the environment. Future research should focus on enhancing speciation analysis through the integration of synchrotron-based methods and advanced spectroscopy for more

precise characterization (Li *et al.,* 2022; Wan *et al.,* 2024). High Spatial Variability of Soil Contamination: The heterogeneous nature of soils at both micro and macro scales hinders accurate assessment of heavy metal contamination. Current sampling techniques often fail to capture the variability adequately (Chen *et al.,* 2022; Świdwa-Urbańska and Batlle-Sales, 2021). Future efforts should prioritize the development of enhanced sampling strategies and geostatistical modeling, utilizing remote sensing and advanced mapping technologies to achieve more accurate spatial assessments (Angelopoulou *et al.,* 2019; Hammam *et al.,* 2022). Long-term Field Monitoring and Predictive Modeling: Laboratory studies, while informative, often do not replicate the complexities of natural environments over extended periods (Wang *et al.,* 2024; Elahi *et al.,* 2023). The long-term behavior of heavy metals, including potential leaching into groundwater or uptake by plants, remains poorly understood. There is a need for extensive field studies combined with robust predictive models that integrate factors such as changing climatic conditions, soil heterogeneity, and metal transformation processes (Bolan *et al.,* 2023; Xiao *et al.,* 2024). Limitations of Current Remediation Techniques: Existing remediation strategies, such as phytoremediation and soil washing, have limitations in efficiency, cost, and environmental impact (Priya *et al.,* 2023; Sánchez-Castro *et al.,* 2023). Phytoremediation, for instance, is time-consuming and depends heavily on plant species and local conditions (Selvi *et al.,* 2019). Future research should explore hybrid approaches that combine biological, chemical, and physical remediation methods, with a focus on nanotechnology-based innovations to enhance the effectiveness of these strategies (Lee *et al.,* 2023). Regulatory Gaps and Inconsistent Policies: Despite growing recognition of heavy metal risks, regulatory standards for soil contamination remain inconsistent across regions, particularly in developing countries (Chen and Ding, 2023). These gaps hinder effective management and mitigation. Future directions should emphasize harmonizing international regulations and fostering interdisciplinary collaboration among scientists, policymakers, and stakeholders to establish standardized guidelines based on scientific evidence (Hinsby *et al.,* 2024). Impact of Climate Change on Heavy Metal Mobility: Climate change introduces additional challenges, as altered precipitation patterns, temperature shifts, and extreme weather events can significantly influence heavy metal mobility and bioavailability (Bolan *et al.,* 2023). Future studies should investigate the synergistic effects of climate change on metal dynamics, integrating climate modeling to predict potential shifts in soil contamination profiles under various environmental scenarios (Xiao *et al.,* 2024). Data Gaps and the Need for Global Monitoring Networks: Significant data gaps persist, particularly in under-researched regions such as parts of Africa and Asia (Haghighizadeh *et al.,* 2024). These gaps impede comprehensive assessments of soil contamination and its impacts. Future research should focus on establishing open-access, global soil contamination databases, facilitating data sharing across regions and institutions to support more effective monitoring and risk assessments (Fernández-Martínez *et al.,* 2024).

CONCLUSION

Heavy metal contamination in soils poses a multifaceted and escalating environmental challenge with far-reaching consequences for ecosystem stability, agricultural productivity, and public health. This review has outlined the intricate geochemical mechanisms governing the behavior of heavy metals in soils, emphasizing the roles of soil mineralogy, adsorption, precipitation, complexation, and redox reactions. These processes are highly dynamic, influenced by environmental factors such as pH, organic matter content, and redox conditions, which collectively determine the mobility, bioavailability, and potential toxicity of metals. A nuanced understanding of these interactions is essential for accurate risk assessment and the development of effective remediation strategies. Despite significant advancements in analytical techniques and geochemical modeling, several challenges persist. The spatial heterogeneity of contaminated soils complicates the accurate assessment of contamination levels, making it difficult to obtain representative data. Furthermore, laboratory-based studies often fail to replicate the complex interactions present in natural environments, limiting the reliability of predictive models. Long-term field studies and the development of advanced speciation techniques, particularly those utilizing synchrotron-based spectroscopy, are necessary to bridge these knowledge gaps and provide more reliable data

for decision-making. The impacts of heavy metal contamination extend beyond soil degradation to affect water quality, plant health, and human well-being. Heavy metals can leach into groundwater, posing risks to drinking water supplies and aquatic ecosystems. The bioaccumulation of metals in crops and livestock further exacerbates food safety concerns, potentially leading to chronic health issues in human. Addressing these risks requires a multidisciplinary approach that integrates soil science, environmental chemistry, public health, and regulatory policy. Innovative remediation technologies such as phytoremediation, bioremediation, and the use of nanomaterials have shown promise in mitigating heavy metal contamination. However, these methods face limitations related to efficiency, cost, and environmental sustainability. Phytoremediation, for example, is time-intensive and highly dependent on plant species and environmental conditions. Emerging hybrid approaches that combine biological, chemical, and physical techniques may offer more robust solutions. Future research should focus on optimizing these methods, exploring the potential of nanotechnology, and evaluating the long-term environmental impacts of remediation efforts. Climate change introduces an additional layer of complexity, as altered precipitation patterns, temperature fluctuations, and extreme weather events can influence the mobility and bioavailability of heavy metals. Predictive models that incorporate climate variables are essential for understanding how contamination profiles may shift in response to changing environmental conditions. This highlights the need for adaptive management strategies that consider both current contamination levels and potential future scenarios driven by climate change. On a policy level, there is a critical need for harmonized regulations and standardized guidelines for soil contamination assessment and remediation. Many developing countries lack stringent regulatory frameworks, hindering effective management and mitigation efforts. International collaboration among researchers, policymakers, and industry stakeholders is vital to develop evidence-based guidelines, promote data sharing, and facilitate the implementation of best practices across regions. Establishing open-access databases for soil contamination data can support this effort by providing a comprehensive resource for researchers and regulators. In conclusion, tackling the issue of heavy metal contamination in soils requires a coordinated global response that leverages scientific innovation, interdisciplinary collaboration, and robust policy frameworks. By advancing our understanding of the geochemical mechanisms of heavy metal behavior, developing scalable and sustainable remediation technologies, and integrating climate resilience into soil management practices, we can work toward safeguarding soil health, protecting ecosystem integrity, and ensuring food security for future generations. This comprehensive approach will not only mitigate the environmental and health impacts of heavy metal contamination but also contribute to achieving broader goals of sustainable development and environmental justice.

AUTHOR CONTRIBUTIONS

M. Kamaraj was responsible for searching the bibliography, selecting the relevant references, coding the references, writing the initial manuscript draft, synthesizing the manuscript, revising the final manuscript version. N. Kiruthika was responsible for writing initial draft, analyzing the references' coding, and reviewing the whole manuscript. T. Saranya was responsible for writing initial draft and review the whole manuscript. J. Aravind was responsible for the selecting the relevant references, analyzing the coding of the references, synthesizing the manuscript, supervision and reviewing the manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Percent
µg/m³	Microgram per cubic meter
AAS	Atomic absorption spectroscopy
As	Arsenic
Bi	Bismuth
Cd	Cadmium
Ca	Calcium
Cr	Chromium
Co	Cobalt
Cu	Copper
DNA	Deoxyribonucleic acid
EDTA	Ethylenediaminetetraacetic acid
Fe	Iron
IVBA	In-vitro bio-accessibility tests
ICP-MS	inductively coupled plasma mass spectrometry
K	Potassium
Hg	Mercury
Mn	Manganese
Mg/m³	Microgram per cubic meter
mg/kg	Milligram per kilogram
mg/L	Milligram per liter
MMT	Manganese tricarbonyl
N	Nitrogen
NH_4NO_3	Ammonium nitrate
P	Phosphorus
pH	Potential of hydrogen
ROS	Reactive oxygen species
SEP	Sequential Extraction Procedures
S	Sulfur
Sb	Antimony
Ti	Thallium
TCLP	Toxicity Characteristic Leaching Procedure
XRD	X-ray diffraction
XRF	X-ray Fluorescence
Zn	Zinc

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