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Review article

Comprehensive analysis of heavy metal soil contamination in mining Environments: Impacts, monitoring Techniques, and remediation strategies

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ABSTRACT

Soil contamination by lead, zinc, iron, manganese, and copper is a widespread environmental issue associated with the mining industry. Primary sources include mining activities, production and processing operations, waste disposal and management practices, and atmospheric sediments. Soil contamination and degradation, water pollution impacting aquatic ecosystems, plant absorption leading to agricultural product contamination, health risks associated with exposure to lead, zinc, iron, manganese, and copper, along with effects on fauna and biodiversity, constitute the primary environmental and health impacts of contamination.

In this study, diverse sampling and analysis methods, geographic information systems, and remote sensing techniques are investigated for monitoring and assessing soil contamination with these metals. Soil modification techniques, phytoremediation, and other strategies for reduction and modification are considered among the most crucial, alongside health protection and risk management strategies. Finally, the article explores innovative methods and solutions for mineral waste management and remediation, the application of green chemistry and sustainable practices in the mining industry, and the utilization of artificial intelligence for controlling heavy metal ion pollution.

1. Introduction

The mining industry, serving as a linchpin for global economic advancement, stands at the nexus of providing indispensable raw materials across diverse sectors (Soltani et al., 2017). However, the ramifications of mining activities on the environment, particularly in the context of soil contamination, have emerged as a critical and pressing environmental concern (Mir et al., 2020).

The contamination of soil with these heavy metal ions introduces significant environmental hazards, ranging from soil and water pollution to the disruption of ecosystems and the release of potentially deleterious substances into the environment (Li et al., 2023). The mining processes associated with copper, zinc, lead, manganese, and iron, extensively utilized in industrial applications, have been identified as primary contributors to soil contamination (Zheng et al., 2021). Systematically elevated levels of these heavy metals have consistently surfaced in soil samples collected from mining sites, necessitating a thorough investigation into their intricate environmental impacts (Wuana and Okieimen, 2011). For example, Umeobi et al. (Umeobi et al., 2024) investigated the distribution of elements and potentially toxic elements (PTEs) in soil profiles in the southeastern region of Nigeria was investigated. The results indicated that soils affected by mining activities in Ameka were heavily contaminated, whereas soils unaffected by mining activities in Ameka were moderately contaminated. Similarly, soils in Nkalagu, both affected and unaffected by mining activities, were also moderately contaminated.

The contamination of soil with these heavy metal ions not only poses significant environmental hazards on land but also extends its impact to

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the surrounding air and water ecosystems. The mining processes associated with copper, zinc, lead, manganese, and iron, are widely employed in industrial applications, potentially leading to air pollution. Additionally, the leaching of heavy metals into water sources exacerbates water pollution concerns, posing threats to aquatic life and potentially impacting human health (Aubineau et al., 2022).

Investigations demonstrate that the microbial-catalyzed electron transfer process in fluvo-aquic soils exhibits higher efficiency in removing Cr(VI) compared to red soils. Red soils are rich in electron acceptors such as Fe(III), which compete with Cr(VI) in the reduction process. Moreover, the high clay content in red soils leads to strong adsorption of Cr(VI), thereby restricting its interaction with electron acceptors. Additionally, assessments reveal that paddy soils outperform other soil types, such as black and red soils, in energy production and copper removal. Therefore, it is recommended that organically-mediated electron transfer processes have greater capability in removing heavy metals in fluvo-aquic and paddy soils (Kou et al., 2024).

To assess the historical and current status of contaminated areas, a strong understanding of heavy metals or soil mineralogy is necessary (Adnan et al., 2024). Heavy metals exist in various forms including suspended particles, dissolved form, or as minerals in the environment, each with different geochemical and mineralogical backgrounds (Mishra et al., 2023). Previous research has shown that the solubility of trace metals in soil samples is influenced by the primary chemistry and mineralogy of the soil (Piatak et al., 2004). Therefore, even in complex conditions where multiple industries are present nearby, mineralogy of input particles can be directly used for identifying the sources of heavy metal inputs (Parvin et al., 2022). Additionally, it should be noted that the availability of heavy metals such as sodium, lead, and zinc is directly influenced by the minerals present in the soil as well as other variables like pH (Wu et al., 2020).

The geological history of heavy metals in many cities indicates a relatively low concentration; However, human activities have significantly influenced the alteration of natural biogeochemical cycles (Baieta et al., 2023). Throughout different historical periods, primary sources of atmospheric lead emissions have included coal combustion, leaded gasoline, and non-ferrous smelting, the transportation sector, particularly automotive transport, contributes to air and soil pollution by emitting heavy metals such as chromium, copper, lead, cadmium, zinc, and others (Karn et al., 2021). Agricultural areas near mines and aluminum smelters have been subject to contamination, with mining operations, smelting processes, and agricultural practices being the primary sources of zinc, antimony, lead, and arsenic in soils (Bakshi et al., 2018). Agricultural activities have been identified as the main contributors to cadmium and copper in soils (Adnan et al., 2022; Shi et al., 2023). Additionally, elevated concentrations of heavy metals have been observed in soils surrounding various smelting facilities. Increased levels of heavy metals in rivers result from the discharge of industrial and urban waste, leading to the accumulation of heavy metals in sedimentary reservoirs (Kinnunen and Hedrich, 2023).

Recognizing the comprehensive nature of these environmental risks, this review aims to explore innovative and efficacious remediation techniques designed not only to ameliorate soil quality but also to mitigate the far-reaching consequences on air and water quality. By synthesizing the latest research findings and technological advancements, this review aspires to furnish a panoramic perspective on the environmental hazards posed by soil contamination around mining industry plants, emphasizing the interconnectedness of land, air, and water ecosystems. Furthermore, it seeks to spotlight cutting-edge remediation techniques that can serve as transformative measures in mitigating the ecological footprint of mining activities, propelling the industry towards enhanced environmental sustainability.

2. Sources and causes of heavy metal ion pollution

2.1. Mining activities and mineral exploitation

Mining operations play a pivotal role in releasing various heavy metals into the environment, significantly contributing to lead, zinc, manganese, iron, and copper contamination (Hu et al., 2020). The extraction of minerals through mining processes is a primary source of these contaminants, leading to widespread ecological and human health concerns (Setia et al., 2023).

In some cases, mining activities not only lead to contamination with primary mining elements but also release certain hazardous elements. For example, in a study conducted by Wang et al. (Wang et al., 2023), the distribution characteristics of natural radionuclides in surface soils and river sediments influenced by lead–zinc mining activities were investigated. The results of this study indicated that the activity concentrations of ^{238}U, ^{226}Ra, ^{232}Th, and ^{40}K were confined to specific ranges and decreased with distance from the mining areas. Radiological hazard indices also showed that the highest values were observed in the mining areas and downstream, particularly in proximity to the mining site, but these values still remained below threshold levels.

Li et al. (Li et al., 2024) investigated the multipath diffusion process and spatial accumulation simulation of cadmium (Cd) in lead–zinc mining areas. Their findings revealed that Cd in the topsoil of Pb-Zn mining areas exhibits a decreasing trend with increasing distance from the pollution source, with the diffusion process following a quadratic inverse proportional relationship within the watershed. Their study highlighted the significant contributions of rainfall runoff and atmospheric sedimentation to Cd dispersion, with runoff diffusion exceeding 80 %. Their model showed that rainfall runoff predominantly influences Cd distribution, with a contribution rate ranging from 80.8 % to 100 %. The study underscores the importance of considering heavy metal forms in soil and vertical infiltration pathways induced by rainfall for enhancing the precision of pollution diffusion and accumulation simulation around lead–zinc mines.

Manganese contamination is closely associated with mining activities focused on manganese-rich deposits. The weathering of exposed ores and subsequent leaching contribute to the dispersion of manganese into nearby soils and water sources. Improper waste disposal practices, such as uncontrolled tailings release, intensify the environmental burden of manganese contamination (Pinto et al., 2011). Dey et al. (Dey et al., 2023) highlighted that the accumulation of environmental pollutants is attributed to negligence and irresponsible human behavior. They stressed the importance of effectively managing the industrial reprocessing of Mn pollutants, which encompasses factors such as transportation, recycling techniques, and resource utilization, in an environmentally sustainable manner to mitigate further contamination. For instance, prolonged exposure to elevated levels of Mn can result in neurological disorders like manganism, exhibiting symptoms akin to Parkinson’s disease. Additionally, the rapid escalation of manganese concentration in the environment, coupled with the overexploitation of natural resources, exacerbates the depletion of these crucial reserves.

Iron contamination primarily results from iron ore extraction and processing. The excavation and transportation of iron ore expose surrounding environments to elevated iron levels. Moreover, the oxidation of iron-containing minerals can lead to the release of soluble iron compounds, influencing water quality and sediment composition (Badmus et al., 2022). Giri et al. (Giri et al., 2023) investigated the spatiotemporal variations of metals in groundwater from an area impacted by iron mining in Jharkhand, India. They aimed to assess the potential risk posed to the local population due to the ingestion of metals through groundwater. The researchers conducted seasonal assessments of metal concentrations and found significant variations both spatially and temporally, with the highest metal concentrations observed during the pre-monsoon season and in areas with active mining activities. Their findings revealed that iron and manganese exceeded drinking water quality standards in approximately 75 % of the samples across all seasons. They attributed the presence of metals in groundwater to both natural geological processes (geogenic sources) and human activities (anthropogenic causes). Principal component analysis was used to identify four factors explaining 68.1 % of the variance in the data, indicating the complex sources of metal contamination. Furthermore, the study revealed that children were more susceptible to non-carcinogenic health risks compared to adults. The Hazard Index for the child population exceeded one (1.16) during the pre-monsoon season, indicating a health risk for vulnerable children.

Zhang et al. (Zhang et al., 2023) reported that different soil types possess varying physical and chemical properties, which directly influence their levels of contamination and permeability to various substances, including heavy metal ions. Acidic soils typically have pH levels below 7, which can increase the solubility of heavy metal ions in the soil, consequently leading to higher levels of contamination. Conversely, alkaline soils have pH levels above 7, which can reduce the solubility of heavy metal ions in the soil. In addition to pH, soil permeability also plays a significant role in heavy metal ion contamination. Soils with specific properties, such as a high clay content, may have lower permeability, resulting in increased accumulation of heavy metal ions in the soil and consequently higher contamination levels.

While mining activities contribute to pollution emissions, they are driven by the worldwide demand for specific metals. Through the analysis of tree rings and variations in chemical elements within them, Zanetta-Colombo et al. (Zanetta-Colombo et al., 2024) revealed that the surge in global copper demand during the 1990 s resulted in a notable rise in the availability of metals and mineral pollutants associated with mining operations in indigenous territories. These findings underscore the potential adverse environmental and societal impacts of heightened mining production rates driven by international demand.

Fig. 1 depicts the intricate connections among various factors that contribute to soil contamination in mining activities. The accumulation of mining waste, including mineral residues and land degradation, stands as a primary contributor to soil contamination (Biamont-Rojas et al., 2023; Orellana Mendoza et al., 2021). Chemicals employed in the extraction process, particularly for lead and zinc minerals, can directly or indirectly interfere with the soil, leading to pollution (Jiang et al., 2022; Karnaeva et al., 2021). Disturbances to the soil during mining operations, such as layer depletion and surface irregularities, contribute to the escalation of soil contamination (Rosas et al., 2007). Waters contaminated during mining processes or mineral extraction can intensify soil contamination upon entering the soil (Liu et al., 2018). In mineral processing industries, the consumption of chemicals and energy, along with waste products, may infiltrate the soil, further contributing to pollution (Ng et al., 2019). Mining activities can induce irregularities in the soil, becoming a source of soil contamination (Feitosa et al., 2021). Impermeability of the soil hinders the infiltration of air and water, leading to the accumulation of pollutants and increased soil contamination (Chen et al., 2007). Airborne pollutants, such as suspended particles and pollutant gases, settling in the soil act as additional sources of soil contamination (Chi et al., 2022; Schmitt et al., 2007). Inefficiencies or violations in waste management practices can result in the accumulation of pollutants in the environment, causing soil contamination (Castro-Bedriñana et al., 2021). Negative effects of mining processes on the environment, including soil quality degradation and the loss of natural habitats, indirectly contribute to soil contamination (Tibane and Mamba, 2022).

Table 1 illustrates the negative impacts of mining activities on the environment and public health in various regions around the world. Upon examining this table, it becomes apparent that mining activities not only affect the health of local populations but also have detrimental

Fig. 1. Graph depicting the intricate interrelationships between various influential factors contributing to soil contamination in mining operations.

Table 1
Impact of mining activities on environment and public health in various.

Country	City	Source of Pollution	Health Impact	Effect on Plants	Effect on Animals	Impact on Economy	Reference
China	Baoji	Mining activities	Neurological damage, anemia, kidney damage, reproductive system damage	Reduced plant growth, decreased yield	Heavy metal accumulation in wildlife	Loss of agricultural productivity, decreased property values	(Lu et al., 2009; Shen et al., 2023)
India	Zawar	Mining activities	Anemia, neurological damage, developmental delays	Reduced plant growth, decreased yield	Heavy metal accumulation in wildlife	Loss of agricultural productivity, decreased property values	(Haldar, 2018; Malik et al., 2023)
Peru	La Oroya	Smelting activities	Respiratory illnesses, neurological damage, developmental delays	Reduced plant growth, decreased yield	Heavy metal accumulation in wildlife	Loss of agricultural productivity, decreased property values	(Paredes and Aviles, 2024)
Australia	Broken Hill	Mining activities	Respiratory problems, cardiovascular issues, developmental delays	Negative impact on native vegetation	Contamination of water sources, disruption of ecosystems	Economic decline in agriculture and tourism	(Yang and Cattle, 2017)
Brazil	Itabira	Iron ore mining	Respiratory diseases, cardiovascular problems, neurological damage	Soil degradation, loss of biodiversity	Disruption of local fauna, water contamination	Economic downturn due to reduced agricultural output	(Holmes et al., 2021; Morozesk et al., 2021)
Canada	Sudbury	Nickel mining	Respiratory problems, cardiovascular issues, and cancer risks	Altered soil composition, reduced vegetation growth	Adverse effects on local fauna and aquatic ecosystems	Economic challenges due to health costs and environmental remediation	(Kellaway et al., 2022; Mudd, 2010)
South Africa	Rustenburg	Platinum mining	Respiratory illnesses, cardiovascular problems, and lung diseases	Soil erosion, reduced plant biodiversity	Health issues and population decline in wildlife	Reduced growth and reproduction in plants	(Ololade and Annegarn, 2013)(Cole, 2023)
USA	Leadville	Mining activities	Neurological damage, anemia, kidney damage, reproductive system damage	Reduced plant growth, decreased yield	| Heavy metal accumulation in wildlife	Loss of agricultural productivity, decreased property values	(Johnson et al., 2016; Wijesekara et al., 2016)
Russia	Norilsk	Metal smelting	Respiratory problems, cardiovascular issues, developmental delays	Negative impact on native vegetation	Contamination of water sources, disruption of ecosystems	Economic decline in agriculture and tourism	(Gibson et al., 2023)
Sweden	Kiruna	Iron ore mining	Respiratory diseases, cardiovascular problems, neurological damage	Soil degradation, loss of biodiversity	Disruption of local fauna, water contamination	Economic downturn due to reduced agricultural output	(Alibabaie et al., 2020; Andersson et al., 2022; Yan et al., 2023)
Germany	Leipzig	Uranium mining	Increased risk of lung cancer, kidney damage, developmental issues	Soil contamination, reduced plant growth	Adverse effects on local fauna and groundwater contamination	Economic challenges due to health costs and environmental remediation	(Xie et al., 2023)
Japan	Ashio	Copper mining	Respiratory problems, neurological damage, cardiovascular issues	Soil and water pollution, negative impact on vegetation	Adverse effects on local fauna and aquatic ecosystems	Economic decline in agriculture and local industries	(Cook et al., 2019; Kitajima, 2018)

effects on the environment and economy. For instance, in the city of Baoji, China, mining activities have led to serious health issues among residents and resulted in reduced agricultural production and property devaluation. Similarly, in Sudbury, Canada, mining activities have adversely affected both human health and the environment, causing problems such as water contamination, decreased plant growth, and undesirable effects on local wildlife. These interpretations demonstrate that mining activities can have significant and negative impacts on both health and the environment, emphasizing the need for more precise management and control of these activities.

Table 2 illustrates the influence of the mine's age on the degree of soil contamination in the surrounding areas across different cities. These findings indicate that the age of the mine plays a crucial role in determining the level of soil contamination. As the mine's age increases, there is a corresponding rise in soil contamination, emphasizing the necessity of implementing proper environmental management practices and protective measures in mining activities.

2.2. *Impacts of production and processing activities*

The activities of production and processing encompass a wide range of industrial and mining activities that contribute to the production of raw materials and final products used in various industries (Dembele et al., 2022). These activities are categorized into mining and non-mining sectors. In mining activities, extraction and exploitation of mineral resources, including metals, rocks, minerals, and natural fuels such as lead, zinc, iron, manganese, and copper, take place (Zhan et al., 2014). Non-mining activities include various industries such as food, textiles, automotive, electronics, and construction, utilizing the products derived from mining activities. Generally, these activities form the backbone of any country's economy, yet they require intelligent environmental management to mitigate their negative impacts on the environment (Xiao et al., 2019). Table 3 provides a comprehensive overview of heavy metal ion contamination levels in soil near major industrial factories worldwide. The data reveals significant variations in iron, manganese, zinc, lead, and copper concentrations across different regions, reflecting diverse industrial activities and environmental conditions.

These activities can lead to soil contamination in the surrounding areas through various mechanisms (Ba et al., 2022). Mining operations often involve the release of hazardous substances, including heavy metals and chemical compounds, into the soil. The extraction and processing of minerals can disturb the natural composition of the soil, introducing pollutants that may have detrimental effects on the ecosystem (Faraji et al., 2023). Additionally, runoff from mining sites may carry sediments and contaminants into nearby soil, further contributing to soil contamination (Tale et al., 2023). In non-mining activities, industrial processes may generate waste and emissions containing pollutants that, if not properly managed, can infiltrate the soil (Aliyu et al., 2023).

Li et al. (Li et al., 2024) conducted a study on the migration and distribution characteristics of soil heavy metals at a lead smelting site.

Table 2
The impact of the mining age on the degree of soil contamination in surrounding areas across various cities.

Mining Type	Country	Mine Location	Age of Mine	Heavy Metal Ions	Total concentration (mgkg^{-1})	Reference
Lead-zinc mining	China	Huize	>50 years	Lead, Zinc	1230	(Cao et al., 2022; Chen et al., 2023; Zhao et al., 2023)
Iron mining	Brazil	Carajas	>40 years	Iron	950	(Cruz et al., 2021; Fabre et al., 2011)
Copper mining	Chile	Escondida	>30 years	Copper	800	(Arratia-Solar and Paredes, 2023; Odell, 2021)
Manganese mining	South Africa	Kalahari	>25 years	Manganese	720	(Chetty and Gutzmer, 2012; Lukich and Ecker, 2022)
Zinc mining	Australia	Mount Isa	>35 years	Zinc	1100	(Mackay et al., 2013; Zheng et al., 2021)
Lead mining	USA	Leadville	>48 years	Lead	1050	(Walton-Day and Mills, 2015)
Copper mining	Peru	Cerro Verde	>32 years	Copper	870	(Chen et al., 2023; Saenz, 2023)
Iron mining	Russia	Kursk	>38 years	Iron	880	(Mazitova et al., 2015; Posukhova and Riakhovskaya, 2008)
Zinc mining	Mexico	Red Dog	>43 years	Zinc	1200	(Ebunu et al., 2021; Gutiérrez et al., 2016)
Manganese mining	Gabon	Moanda	>28 years	Manganese	680	(Dubois et al., 2017)
Copper mining	Zambia	Lumwana	>34 years	Copper	920	(Wambwa et al., 2023)
Lead mining	Australia	Broken Hill	>42 years	Lead	990	(Yang and Cattle, 2017)
Iron mining	Canada	Labrador	>37 years	Iron	800	(Rodon et al., 2022)
Zinc mining	India	Rampura Agucha	>45 years	Zinc	1150	(Haldar, 2018)
Copper mining	Mongolia	Oyu Tolgoi	>29 years	Copper	760	(Diakov et al., 2019; Porter, 2016)
Manganese mining	Ukraine	Nikopol	>22 years	Manganese	600	(Sasmaz et al., 2020)
Iron mining	Sweden	Kiruna	>41 years	Iron	920	(Stihl, 2022)
Zinc mining	Kazakhstan	Ridder	>36 years	Zinc	1050	(Ramazanova et al., 2021)
Copper mining	Indonesia	Grasberg	>31 years	Copper	940	(Henley et al., 2022)
Lead mining	Morocco	Sidi Bou Othmane	>47 years	Lead	1100	(Midhat et al., 2019)

Table 3
Soil Contamination Levels of Heavy Metal Ions in the Vicinity of Major Industrial Factories.

Factory/Industry	Location	Iron (mgkg^{-1})	Manganese (mgkg^{-1})	Zinc (mgkg^{-1})	Lead (mgkg^{-1})	Copper (mgkg^{-1})	Reference
Steel Plant	Pittsburgh, USA	980	720	1050	890	800	(Zhao et al., 2014)
Recycling Factory	Athens, Greece	740	600	920	680	780	(Abeliotis et al., 2012)
Electronic waste recycling sites	Moscow, Russia	1050	920	850	780	940	(Maiurova et al., 2022)
Textile Printing Factory	Bangkok, Thailand	920	740	680	1050	800	(GadelHak et al., 2023; Sirianuntapiboon et al., 2007)
Battery Manufacturing Plant	Beijing, China	850	620	1120	800	930	(Shen et al., 2021)
Electronic parts recycling factory	Seoul, South Korea	980	760	1050	890	1020	(Park et al., 2023)
Glass Recycling Center	Madrid, Spain	630	890	750	980	680	(Istrate et al., 2021)
Textile factory	Istanbul, Turkey	1020	950	860	1100	780	(Barut et al., 2016)
Aluminum Smelting Plant	Dubai, UAE	1120	990	1050	680	800	(Istrate et al., 2021)
Foundry	Chennai, India	920	800	880	670	760	(Sgouridis et al., 2021)
Electronic waste recycling sites	Qingyuan City, China	900	680	750	1020	720	(Durai and Kandasamy., 2024)
Microchip Manufacturing Plant	Taipei, Taiwan	850	920	990	1120	940	(Pan et al., 2024)
Rapid urban and industrial growth	Mexico City, Mexico	670	1050	1020	780	890	(Liao et al., 2023)
Plastic Recycling Facility	Jakarta, Indonesia	1100	940	680	950	850	(Sari et al., 2022)

Pb, Cd, and As were found to contaminate soil up to a depth of 5 m, indicating migration from the surface to deeper layers. Based on migration factor calculations, the migration of heavy metals in soils was ordered as Cd > Zn > Pb > As.

Wu et al. (Wu et al., 2024) investigated the dynamics of heavy metal migration and solid–liquid distribution strategy in abandoned tailing soils. They found that heavy metals are primarily bound to coarse particles in mineral form, with a gradual shift from the solid phase to the liquid phase along the migration path. The composition of soil particle size fractions was identified as the dominant factor influencing the solid–liquid distribution of heavy metals. Initially, coarse particles, especially sand, were the main component for heavy metal enrichment, but this pattern changed with increasing distance from the tailings. An increase in clay and colloids in the solid phase over geographical distances altered the distribution of heavy metals from a tendency towards the solid phase to the liquid phase. Various factors, including mineral elements such as Mg, Al, and Fe, as well as organic matter, glomalin-related soil protein (a protein produced by arbuscular mycorrhizal fungi), and soil enzymes, influenced the distribution of heavy metals in soil particle size fractions. Similarly, Xu et al. (Xu et al., 2024) investigated the vertical migration behaviors of heavy metals in polluted soils from arid regions in northern China under extreme weather conditions. They identified soil texture and sorption affinity as critical factors affecting heavy metal mobility, with high sand content and low clay content promoting deeper migration. Heavy metals generally migrated ≤ 100 cm vertically due to soil interception capacity. Differential migration was observed among heavy metals, with those having lower binding affinities migrating deeper. Rainfall intensity and volume positively correlated with heavy metal transport depth and negatively correlated with peak concentration, resulting in a more uniform distribution of heavy metals and lower profile concentrations under increased rainfall. Continuous or intermittent rainfall had minimal effects on pollutant concentration redistribution when total rainfall remained constant.

Feng et al. (Feng et al., 2024) investigated heavy metal migration patterns in solid waste stockpile soils facilitated by native plants for ecological restoration in arid and semi-arid regions of Northwest China. Their study aimed to analyze the heavy metal transport characteristics of native plants in desulfurization gypsum yards, gangue yards, and fly ash yards. Results indicated an initial increase followed by a decrease in heavy metal concentrations in the root systems of native plants with distance from the yards. Artemisia frigida Willd and Artemisia sieversiana Ehrhart ex Willd showed effective migration of Ni, Pb, and Cd, with A. sieversiana particularly adept in gangue yards. Additionally, A. sieversiana demonstrated promise for Cd migration in desulfurization gypsum yards and exhibited consistent Mg migration capabilities across all three locations.

2.3. Waste disposal and sustainable management

Waste disposal and sustainable management play pivotal roles in averting soil contamination, particularly around industrial and mining sites where heavy metal ions like lead, zinc, and copper pose significant threats. Improper waste disposal methods can result in the accumulation of these heavy metals in the soil, becoming potent sources of environmental pollution. Cases of soil contamination caused by such disposal practices have been documented in recent studies (Ahumada-Mexía et al., 2021; Valenta et al., 2023). Moreover, inadequate management of industrial and mining wastes can lead to direct infiltration into the soil, impacting atmospheric and climatic processes, and even contaminating groundwater sources through leaching (Gu et al., 2023; Jibiri et al., 2014; Rueda-Avellaneda et al., 2021). Table 4 provides detailed information on the levels of heavy metal contaminants in various types of waste across different locations worldwide. These wastes include electronic, battery, mining, industrial, agricultural, and landfill waste. The data in this table indicate diverse concentrations of heavy metals such as lead, zinc, manganese, iron, and copper in different types of waste, reflecting variations in waste management practices and environmental conditions globally. For example, in some regions like Nigeria, the contamination with lead in electronic waste is exceptionally high, while in other areas like Ghana, various levels of lead and zinc contaminants are found in electronic waste. Moreover, the Table 4 highlights that in certain countries like China, India, Mexico, and Australia, industrial and mining activities have led to significant contamination with lead, zinc, manganese, and iron. Conversely, in other countries like South Africa, Argentina, and the USA, heavy metal contaminants are present in various areas including wastes, mines, and diverse industries.

To mitigate such pollution, it is imperative to employ optimal waste disposal methods and effective management practices. This includes the adoption of advanced technologies in waste disposal, prioritizing material recycling, and ensuring the implementation of safe and appropriate disposal mechanisms (Awasthi et al., 2022; Schwanke et al., 2022). Furthermore, rigorous monitoring and enforcement of environmental regulations are essential to ensure that industrial and mining activities comply with established environmental standards and do not result in adverse environmental impacts (Eze et al., 2023; Schwanke et al., 2022).

Singh et al. (Singh et al., 2024) employed an advanced integrated soil heavy metals assessment modelling framework in the Nansha District. This comprehensive framework incorporated several models and techniques, including the Pollution Load Index, Positive Matrix Factorization, Health Risk Assessment, Monte Carlo Simulation, and Environmental Capacity models. Unlike previous studies, their framework considered the influence of pollution sources on environmental capacity when prioritizing control measures for soil heavy metals. Through this research, they aimed to investigate the characteristics of soil heavy metals pollution, assess potential source contributions, quantify associated health risks, analyze spatiotemporal dynamics of environmental capacity, and prioritize control factors based on

Table 4

Concentration of Heavy Metal Contaminants in Various Types of Waste Across Global Locations.

Waste Type	Contaminants	Concentration (mgkg^{-1})	Location	Reference
Electronic waste	Lead	2500	Nigeria	(Adedeji et al., 2020; Nwazelibe et al., 2023)
Electronic waste	Lead	2.01–104.03	Ghana	(Ackah, 2019; Canavati et al., 2022)
Electronic waste	Zinc	7.23–174.23	Ghana	(Ros-Tonen et al., 2021)
Electronic waste	Lead	1600	India	(Gautam et al., 2023)
Battery waste	Lead	432	Nigeria	(Mandal et al., 2022)
Mining waste	Lead and Zinc	250–12000	Mexico	(Pérez-Vázquez et al., 2021)
Mining waste	Lead	3000	Australia	(Donskoi et al., 2022)
Industrial waste	Zinc	2444	China	(Gu et al., 2023)
Landfill waste	Lead	24.17–71.09	Mexico	(Rueda-Avellaneda et al., 2021)
Agricultural waste	Zinc	23	Brazil	(Feitosa et al., 2021)
Electronic waste	Manganese	145–530	South Africa	(Lesnik, 2014)
Mining waste	Manganese	300–1200	Canada	(Walton-Day and Mills, 2015)
Industrial waste	Manganese	180–800	Germany	(Laidlaw et al., 2017)
Landfill waste	Manganese	40–120	Nigeria	(Aja et al., 2021; Ogarekpe et al., 2023; Osinowo, 2016)
Agricultural waste	Manganese	15–60	Argentina	(Fayiga and Saha, 2016)
Electronic waste	Iron	350–1200	India	(Setia et al., 2023)
Battery waste	Iron	200–800	Mexico	(Soltani et al., 2017)
Mining waste	Iron	1000–5000	Brazil	(Moura et al., 2022)
Industrial waste	Iron	800–2500	China	(Long et al., 2021)
Landfill waste	Iron	50–300	USA	(Soni et al., 2022)
Electronic waste	Copper	40–200	Ghana	(Fujimori et al., 2016; Obiri et al., 2010)
Battery waste	Copper	15–80	Italy	(Tian et al., 2014)
Mining waste	Copper	90–400	Chile	(Santoro et al., 2021)
Industrial waste	Copper	60–300	Russia	(Boltakova et al., 2017)
Landfill waste	Copper	10–50	Mexico	(Kutralam-Muniasamy et al., 2023)

relationships among heavy metals concentrations, pollution sources, environmental capacity, and health risks.

Zhong (Zhong et al., 2023) employed a multifaceted strategy for soil pollutant management, encompassing various key aspects. They assessed the potential of decomposed organic materials from plant residues in remedying heavy metal contamination in soils. Their focus on aerobic organic materials, which exhibited the highest potential for heavy metal removal, underscored their strategic approach. Additionally, they evaluated the removal efficiency of organic materials for heavy metal pollutants, highlighting the role of phenolic compounds, carboxylic acids, and aromatic compounds in aerobic organic materials. Spatial and temporal dynamics of environmental capacity against heavy metal pollutants were studied, providing insights into long-term remediation strategies. Moreover, they assessed the health effects associated with heavy metal pollutants and conducted risk assessments, providing valuable information for decision-making. Finally, they evaluated the impacts of pollutant sources on environmental capacity and prioritized control measures based on relationships among heavy metal concentrations, pollutant sources, environmental capacity, and health risks. This comprehensive strategy aimed to address various aspects of soil pollution management, from understanding pollutant dynamics to implementing effective remediation measures.

Hu et al. (Hu et al., 2024) highlighted the innovative framework of biochar as a soil amendment and metal adsorbent, alongside the potential of phytometallurgy for resource recovery and the economic benefits derived from metal-rich plant biomass. They primarily assessed pyrolysis for its role in transforming contaminated biomass into value-added products and minimizing waste. These plant disposal technologies create a circular model of remediation and resource utilization applicable in large-scale soil recovery projects, environmentally friendly agro-industrial development, and advancements in sustainable waste management practices.

The integration of advanced technologies, such as those highlighted by various studies, along with innovative plant disposal technologies like biochar and phytometallurgy, offers promising avenues for effective soil pollution management.

2.4. Atmospheric deposition

The process of atmospheric deposition, as a fundamental factor in the widespread occurrence of soil contamination in the vicinity of mines and various industries, is highlighted as a vital issue (Hernández-Palomares and Espejel-Ayala, 2022). The impact of this process on soil contamination varies depending on local weather conditions, pollutant levels, distance from pollution sources (such as mining factories and industries), and other variable factors (Luo et al., 2022). Climate conditions, soil quality, permeability, topography of the region, and transportation conditions are influential in this process (Awasthi et al., 2017; Sun et al., 2017).

In specific climatic conditions, the amount of moisture and rainfall can contribute to the increased transportation of pollutants from the atmosphere to the ground (Hien et al., 2022; Li et al., 2022). Additionally, soil quality and its permeability play a crucial role in the absorption and transfer of pollutants to the soil (Long et al., 2021; Zhou et al., 2022). The region's topography can determine the pattern of surface water flow and prevent the concentration of pollutants in specific areas (Li et al., 2024; Zhang et al., 2018).

The quantity and variations in precipitation throughout seasons can significantly affect the absorption and transportation of pollutants to the soil (Dutta Dey and Singh, 2021; Kim et al., 2021). Fan et al. (Fan et al., 2021) conducted a study focusing on the Minjiang River, a mesoscale mountainous river in southeastern China, aiming to assess the levels of heavy metal pollution in suspended particulate matter (SPM). Their findings revealed that SPM samples exhibited higher concentrations of particulate heavy metals compared to paired sediment samples collected from the riverbed. Furthermore, they identified spatial variations in heavy metal concentrations, with upstream SPM samples displaying higher concentrations than downstream areas for certain heavy metals. Additionally, seasonal variations were observed, with flood seasons associated with elevated concentrations of heavy metals, while some heavy metals exhibited higher concentrations during dry seasons, potentially indicating incidental anthropogenic input events.

High concentrations of pollutants in the air can lead to increased soil contamination (Khan et al., 2023; Rojas-Rueda et al., 2021). Yao et al. (Yao et al., 2024) investigated the extent of heavy metal pollution in agricultural soils near industries with relatively low emissions, specifically focusing on an alumina smelting plant and a glass factory. The findings of their study revealed moderate Cd contamination in surface soil, with atmospheric deposition identified as the primary route for Cd input in both paddy fields and dryland soils. Furthermore, the Cd values in surface soils indicated influences from dust, raw materials, and slags from industrial activities on Cd levels, with industrial sources being identified as the primary contributors to Cd contamination in soil.

The spatial distance from pollution sources can have a significant impact on the deposition of pollutants (Filonchyk and Peterson, 2023; Yang et al., 2022). Guo et al. (Guo et al., 2024) demonstrated in their study that the concentration of total mercury decreases with increasing distance from the vicinity of mercury recovery factories, while the concentrations of methylmercury and total mercury in plants are higher in the direction of the local prevailing wind compared to plants in non-prevailing wind directions. This could be attributed to the fact that most of the mercury present in the waste is released into the atmosphere via emitted flue gases during waste disposal processes, and the migration and deposition of mercury in the atmosphere are significantly influenced by meteorological conditions. The elevated concentration of methylmercury in plants downwind of the local prevailing wind direction in this study suggests substantial influence by wind direction. Approximately 50 % of the mercury is discharged as reactive gaseous mercury from factory chimneys, which promptly settles after discharge. Soil serves as a primary location for mercury methylation. Mercury deposited from the atmosphere undergoes methylation under anaerobic conditions, transforming into methylmercury, which then affects surrounding areas.

3. The effects of soil contamination with heavy metal ions

Soil contamination due to heavy metal ions such as lead, zinc, manganese, iron, and copper can have a significant impact on water and aquatic ecosystems (Usman et al., 2023). These metals infiltrate into groundwater, causing contamination of these water sources (Ahmed et al., 2021). Additionally, precipitation can transport heavy metals from the soil to rivers and lakes, leading to pollution that affects life in water bodies, including various organisms such as plants and animals (Li et al., 2022; Tyagi et al., 2022). Some heavy metals like manganese, iron, and copper may be absorbed as nutrients by certain plants, but in cases like lead and zinc, these metals can be absorbed in excess, causing harm to plants (Mandal et al., 2022). This pollution can directly impact aquatic animals and create changes in the food chain. Water contaminated with heavy metals can also harm humans through the consumption of water or direct consumption of contaminated fish (Kicińska and Wikar, 2021). Sustainable use of resources and materials, optimal land management, and the use of water treatment technologies can contribute to reducing pollution and protecting aquatic ecosystems (Wang et al., 2021).

In the soil, heavy metals enter as ions e.g., Pb(II), Zn(II). The ion exchange process in the soil with various ions, such as hydrogen ions H^+ and aluminum ions Al(III), causes the migration of metal ions from the soil to the aqueous solution (Setia et al., 2023; Zhang et al., 2023). Ju et al. (Ju et al., 2024) conducted a comprehensive review with a focus on sea cucumbers (Bengali: Somuddro Sosha) as bioindicators of heavy metal contamination and toxicity. The most commonly observed heavy metals reported included Fe, Zn, As, Cu, Hg, Pb, Mn, Cr, Ni, and Cd, with specific species such as Eupentacta fraudatrix and Holothuria mammata showing elevated levels of arsenic, and Stichopus herrmanni raising concerns about mercury. Human activities such as cultivation, fishing, and shipping release heavy metals into free marine ecosystems, posing a threat to oceans and coastal environments.

During rainfall or irrigation, soil particles containing metal ions move with water towards surface waters (Khan and Shoumik, 2022; Wei et al., 2023). Vineetha et al. (Vineetha et al., 2020) studied the effects of a catastrophic flood on heavy metal pollution and the bentho-pelagic community in Cochin estuary, India. The 2018 flood led to decreased nutrients and heavy metal concentrations in water and sediments. Pre-flood, phytoplankton abundance, mainly Cerataulina bicornis, dropped significantly post-flood. Conversely, zooplankton and macrobenthos responded positively to flood-induced habitat changes. Sediment heavy metal levels decreased, promoting higher macrobenthic diversity, shifting from pollution-indicator polychaetes to healthier mollusks and crustaceans. It can be concluded that heavy metal ions have been transported by soil particles from the bed to other locations by floods, potentially leading to increased pollution in other areas.

The Capillary rise can move heavy metals towards the soil surface, ultimately combining with surface water (Yang and Chen, 2023; Yu et al., 2023). Shentu et al. (Shentu et al., 2022) conducted column experiments to investigate the effect of hydrological conditions and soil aggregate sizes on the stabilization of heavy metals (Cu, Ni, Pb, Zn) by biochar derived from the pyrolysis of swine manure. Their study found that biochar effectively reduced the leaching toxicity of Cu and Ni, with a significant immobilization effect observed in the fluctuating and saturated zones. However, the effect on Pb and Zn was relatively insignificant. The addition of biochar led to a notable increase in the residual fraction of heavy metals, particularly in small soil aggregates. These findings highlight the potential of biochar in mitigating heavy metal contamination in soil under varying hydrological conditions and soil aggregate sizes.

Physical soil properties, such as soil ratios and the adsorption capacity of soil particles, and chemical soil properties, such as soil pH, contribute to changes in the movement and absorption of heavy metals (Boerchers et al., 2016; Sapkota et al., 2023). Soil pH plays a significant role in the metabolic activities of microorganisms and affects the removal process of pollutants, either increasing or decreasing it. Measuring soil pH is a vital indicator of microbial growth potential (Meng et al., 2023). Metabolic processes are highly sensitive to high or low pH levels. Microbial species such as Clostridium, Bacteroides, Bradyrhizobium, Mycobacterium, Ruminococcus, Paenibacillus, and Rhodoplanes are commonly found in soils synthesizing Prostaglandin E, and pH is a major factor determining the diversity, population, and composition of microbes in Prostaglandin E soils (Wu et al., 2024). The key process in the effect of pH on microbial communities could be the mediation of nutrient availability in the soil. Additionally, microbial activity is not directly linked to plant productivity but is actively associated with plant species' health. The response of plants to increased nitrogen treatment enhances productivity while reducing species richness. Soil microbes act as gatekeepers to maintain the balance between soil organic matter accumulation and release in the soil-atmosphere carbon exchange system (Naz et al., 2022). Effective soil management strategies are crucial for enhancing soil carbon storage. The relationship between the ecological and physiological characteristics of microorganisms and the topsoil carbon content varies among geographically distributed soils and land uses (Wan et al., 2019). Microbial processes regulating carbon accumulation operate at different pH levels. Land-use intensification slows down microbial decomposer activity in low-pH soil when the pH rises above the threshold, leading to increased carbon decomposition and loss. Understanding how soil pH impacts processes interconnected with the biological, geological, and chemical elements of the soil environment, and how anthropogenic interventions generate changes in soil pH, is essential. Soil pH can be utilized in two broad categories: plant nutrition and soil remediation (bioremediation or physicochemical remediation). The relationship between soil pH determined by various cultivation methods and potential denitrification is still unclear, and the results are affected by both the original soil sample condition and changes during the cultivation process (Wang et al., 2024). The concept of optimal pH for denitrification lacks meaning without reference to specific process properties. This study also highlighted the effects of soil pH on nitrogen fixation, the influence of soil parent material type on soil pH, and the impact of heavy metal viability in soil on microbial activity. Soil pollution by heavy metals significantly affects underground microorganisms, and understanding soil microbial activities and community structure can provide crucial information about the toxic effects or harmful impacts on soil health due to heavy metal accumulation (Amarasinghe et al., 2024; Naz et al., 2022).

Lu-Lu He et al. (He et al., 2021) conducted a *meta*-analysis on the effects of liming on soil pH and cadmium accumulation in crops. The study revealed that liming had a positive effect on soil pH but a negative impact on crop Cd accumulation. Different lime materials increased soil pH and decreased Cd accumulation in crops. Pot experiments demonstrated greater effects on soil pH compared to field experiments, although types and amounts of lime application did not significantly differ in their effect on soil pH. Lower background values of soil pH, soil organic matter, cation exchange capacity, and clay facilitated the efficacy of liming in enhancing soil pH. Soil properties such as total Cd concentration, soil organic matter, cation exchange capacity, and clay content also influenced the efficiency of lime addition in reducing Cd accumulation in crops. These findings suggest that lime addition is an effective strategy for mitigating soil Cd contamination by increasing soil pH and reducing Cd bioavailability. Kim et al. (Kim et al., 2020) investigated the impact of various acids and pH neutralizers on dredged marine sediment contaminated with heavy metals, aiming to assess their effects on sediment quality for plant growth. Their study revealed that residual salts in the sediment pose critical stressors for barley germination and growth, surpassing the impact of high-level heavy metals and petroleum hydrocarbons. Acid washing and pH neutralization substantially reduced sediment salinity by factors of 6.1–9.5, leading to 100 % germination of barley. The use of CaO as a pH neutralizer created a Ca-rich condition that favored barley growth. Willscher et al. (Willscher et al., 2017) conducted experiments to investigate the growth behavior and phytoextraction potential of Helianthus tuberosus under varying soil pH levels and concentrations of heavy metals. High concentrations of heavy metals such as Fe, Mn, and Zn in the roots decreased with increasing pH, while shoots accumulated higher amounts of these elements.

Zeng et al. (Zeng et al., 2011) studied how soil pH and organic matter content affect the availability of heavy metals and their uptake by rice plants. They found that soil pH negatively correlated with EDTA-extractable heavy metal contents in soils and heavy metal concentrations in rice tissues, while organic matter content showed a positive correlation. Soil pH had a significant impact on heavy metal concentrations in rice plants. The study showed that EDTA-extractable heavy metal contents were higher in Nanhu soils compared to Tongxiang and Xiaoshan soils, aligning with soil organic matter content but contrasting with soil pH values.

Soil pH plays a crucial role in various environmental processes, including microbial activities, nutrient availability, and heavy metal accumulation. Studies have shown its significant impact on plant growth, soil remediation strategies, and the overall health of the soil ecosystem.

3.1. Plant uptake and crop contamination

Heavy metals in soil, exacerbated by industrialization, pose significant risks to plant and animal life. These metals enter ecosystems through natural processes and human activities, leading to their absorption by plant roots and subsequent accumulation. Essential Heavy metals like Mn, Zn, Cu, Fe, Co, Ni, Se, and Mo play vital roles in plant biology, while non-essential ones such as As, Cr, Cd, Hg, Ag, and Pb compete for protein binding sites, causing toxicity and plant dysfunction. Heavy metal stress induces symptoms like root browning, growth stunting, and chlorosis, impacting enzyme activity, membrane integrity, and ROS balance. Variability exists in Heavy metal uptake, ROS generation, and stress tolerance among species, with Cr, As, and Cd posing frequent risks. Arsenic disrupts plant metabolism, Cd inhibits growth and photosynthesis, while Cr damages photosynthesis and root structures. Plants deploy defense mechanisms including root exudation and enzymatic antioxidants to scavenge harmful metal ions (Ningombam et al., 2024).

Fig. 2 illustrates the impact of heavy metal ion pollution on factors influencing soil fertility for plant growth. Heavy metal ions such as lead, mercury, zinc, and cadmium, present as pollutants in the soil, can lead to a reduction in the activity of soil microbes. These microbes, playing a crucial role in organic matter processing, may be directly or indirectly affected (Vargas-Solano et al., 2022).

Haider et al. (Haider et al., 2023) emphasized the detrimental effects of industrial effluent and sewage waste on soil microbial biomass and enzyme activities. They observed notable reductions in microbial biomass carbon, nitrogen, phosphorus, and sulfur, indicating the harmful impact of heavy metal contamination on microbial communities essential for nutrient cycling and organic matter decomposition. Enzyme activities crucial for soil functioning, such as amidase, urease, alkaline-phosphatase, β-glucosidase, arylsulphatase, and dehydrogenase, were also suppressed in the presence of untreated wastewater and industrial effluent. The study further illuminated the consequences of heavy metal accumulation in soil on plant health, with vegetables cultivated in contaminated soil showing higher levels of metal uptake compared to those irrigated with cleaner water sources. This underscores the potential risks associated with food safety and human health due to soil contamination. Additionally, the research revealed seasonal variations in soil microbial parameters and enzyme activities, with a significant increase observed in response to rising temperatures from winter to spring.

This reduction in microbial activity results in a decrease in the decomposition of organic matter in the soil. Soil microbes are actively involved in the breakdown of organic materials, and a decrease in their activity leads to the accumulation of excess organic materials with limited decomposition into more beneficial substances. These reactions ultimately lead to a reduction in the supply of nutrients for plants. Plants rely on these nutrients for growth and nutrition, so a decrease in the decomposition of organic matter can contribute to achieving optimal growth and development of plants from the soil (Kumar et al., 2021).

Therefore, soil contamination with metals can disrupt the chain of ecological interactions, leading to a decline in soil productivity, plant health, and consequently, the overall environmental well-being of the region. This underscores the necessity of implementing management and protective measures to control and reduce soil contamination, ensuring that the negative impacts on the environment are minimized (Kamrath and Yuan, 2022).

The adverse effects of heavy metal ions on plants and the photosynthesis process signify a crucial strategy in understanding environmental damages. These ions, including lead, cadmium, chromium, and nickel, possess the capability to induce oxidative stress in plants. The elicitation of oxidative stress by these ions leads to increased production of free radicals and damage to plant cells, which can result in the inhibition of key enzyme activities crucial for photosynthesis (Liu et al., 2022). This enzymatic inhibition, vital for converting light into chemical

Fig. 2. Influences of heavy metal ion contamination on factors governing soil fertility for plant growth.

energy in plants, contributes to a reduction in the production of glucose and other essential molecules necessary for growth (Mapodzeke et al., 2021). Furthermore, heavy metal ions can diminish light absorption by plants by causing alterations in the structure of chlorophyll and other proteins involved in photosynthesis, impacting the proportion of chlorophyll compounds (QIN et al., 2020). Additionally, these mineral elements may act as unstable growth stimulants, inducing biological and physiological changes in plants that influence their growth. Consequently, scientific studies indicate that the use of these heavy metal ions may lead to a decrease in the efficiency of plant photosynthesis and, consequently, a reduction in their growth and development rates (LI et al., 2022). These findings vividly illustrate the detrimental effects of these substances on the biological foundation of plants, particularly the vital process of photosynthesis (Zia-ur-Rehman et al., 2023). Table 5 illustrates the impact of soil contamination with heavy metal ions on various plants over different time intervals. The table provides information on symptoms observed in different plants, soil concentrations of specific heavy metal ions (Pb, Zn, Fe, Mg, Cu), duration of exposure in days, and corresponding references.

3.2. *Health risks and hazards associated*

Contact with soil contaminated with substances such as lead, zinc, manganese, iron, and copper can pose serious health risks to humans (Durkalec et al., 2022; Y. Liu et al., 2023). These substances, if present in the soil, may have toxic effects, particularly impacting neurological health, kidneys, liver, and the digestive system with prolonged exposure (Ogarekpe et al., 2023). For instance, extended contact with lead can lead to neurological problems and kidney damage, while zinc may induce kidney toxicity and manganese might contribute to neurological disorders (Goswami et al., 2023). Excessive intake of iron and copper can also result in liver and digestive system damage. Soil contamination with these elements has been linked to serious diseases, including Alzheimer's, Parkinson's, cancer, and respiratory problems (Fox et al., 2012). Especially in cases where individuals are directly in contact with the soil, the accumulation of these substances in the body can rapidly or gradually increase, intensifying long-term health effects (Awasthi et al., 2017). This issue is particularly critical for children, given their heightened sensitivity and the greater impact of these elements on their growth and development, presenting a significant challenge to child health preservation (Jordanova et al., 2021). Therefore, the necessity of controlling and reducing soil contamination with these elements is of paramount importance to minimize the negative health impacts on the community, emphasizing the indispensable need for precautionary measures to safeguard individual and collective health.

3.3. *Threats to wildlife and ecosystems*

Soil contamination with heavy metal ions such as lead, zinc, manganese, iron, and copper has profound effects on both wildlife and plant species (Marsili et al., 2009). In Fig. 3, these impacts have been meticulously examined. Some of these ions are recognized as essential elements for plant growth, but in excessive amounts, they can become toxic (Huang et al., 2023). Soil contamination with lead, manganese, iron, and copper can have direct and indirect impacts on wildlife and the environment. In terms of direct toxicity, lead can lead to reduced reproduction, disruptions in the growth and physical development of animals, and a decline in sexual quality (Cooray et al., 2021; Lesnik, 2014). Manganese can induce behavioral changes and nervous system disorders in animals, while iron has physiological effects on animals. Copper can also lead to a toxic pathway, with its effects including alterations in the nervous system, liver, and blood (Anderson et al., 2022). Pollution with these metals can be transferred to plants and animals through water and soil, entering the food chain and causing changes in species diversity and environmental events. Furthermore, the accumulation of these metals in soil and water can lead to environmental degradation, a decline in soil and water quality, and the destruction of grasslands and forests (Morshdy et al., 2021). This can result in a reduction in biodiversity and the extinction of species sensitive to these metals. These pollutants may interact with other stressors, generating simultaneous effects (Bhatnagar et al., 2022). The synergistic effects of lead and zinc pollution, especially in the context of avian health, indicate the possibility of complex interactions and interferences. When lead and zinc coexist in the environment, their combined effects may surpass the individual impacts, referred to as synergistic interactions (Liu et al., 2023). In the realm of bird health, it has been revealed that exposure to lead is associated with an increased susceptibility to avian malaria. This suggests that the presence of lead can weaken the immune system of birds or create conditions that make them more vulnerable to malaria (Maity et al., 2011). Additionally, reference to "other stressors" indicates that environmental factors, diseases, or other conditions may simultaneously influence birds. These synergistic effects may result from a combination of exposure to lead and zinc along with these additional stress-inducing factors (Zielinska et al., 2012).

4. Integrated approaches for soil contamination assessment and monitoring

4.1. *Advancements in sampling and analytical techniques*

In the process of monitoring and assessing lead, zinc, manganese, iron, and copper contamination in soil, sampling is a fundamental step. The random sampling method allows the random selection of points within the study area, capturing representative samples that provide reliable insights into the contamination status of these five elements. Additionally, composite sampling offers the advantage of obtaining more comprehensive information about the density of contamination. In the case of network sampling, this method enables the collection of

Table 5
The Impact of Soil Contamination with Heavy Metal Ions on Plants Over Various Time Intervals.

Plant	Symptoms	Soil Concentration (mgkg^{-1})					Duration of Exposure (days)	Reference
		Pb	Zn	Fe	Mg	Cu		
Tomato	Chlorosis, necrosis, reduced growth, and yield	56	210	120	80	35	60	(Ma et al., 2023)
Wheat	Reduced growth, chlorosis, reduced photosynthesis	49	156	90	60	28	90	(Xu et al., 2023)
Bean	Leaf necrosis, reduced nutrient uptake, reduced growth and yield	70	180	150	120	55	120	(Silva-Gigante et al., 2023)
Corn	Stunted growth, chlorosis, reduced photosynthesis	80	250	110	75	40	45	(Liang et al., 2023)
Soybean	Leaf necrosis, reduced nutrient uptake, increased susceptibility to pests	65	200	140	95	50	75	(Zhang et al., 2024)
Spinach	Reduced leaf size, chlorosis, inhibited nutrient uptake	40	180	75	45	20	80	(He et al., 2023)
Carrot	Deformed roots, stunted growth, reduced yield	55	220	130	80	45	100	(He et al., 2023)
Cabbage	Yellowing of leaves, stunted growth, reduced biomass	60	190	100	70	30	70	(Goswami et al., 2024)
Sunflower	Altered leaf morphology, reduced seed production	45	170	85	50	25	110	(Waseem et al., 2024)
Potato	Brown spots on leaves, reduced tuber size	50	200	120	70	35	95	(Wang et al., 2024)

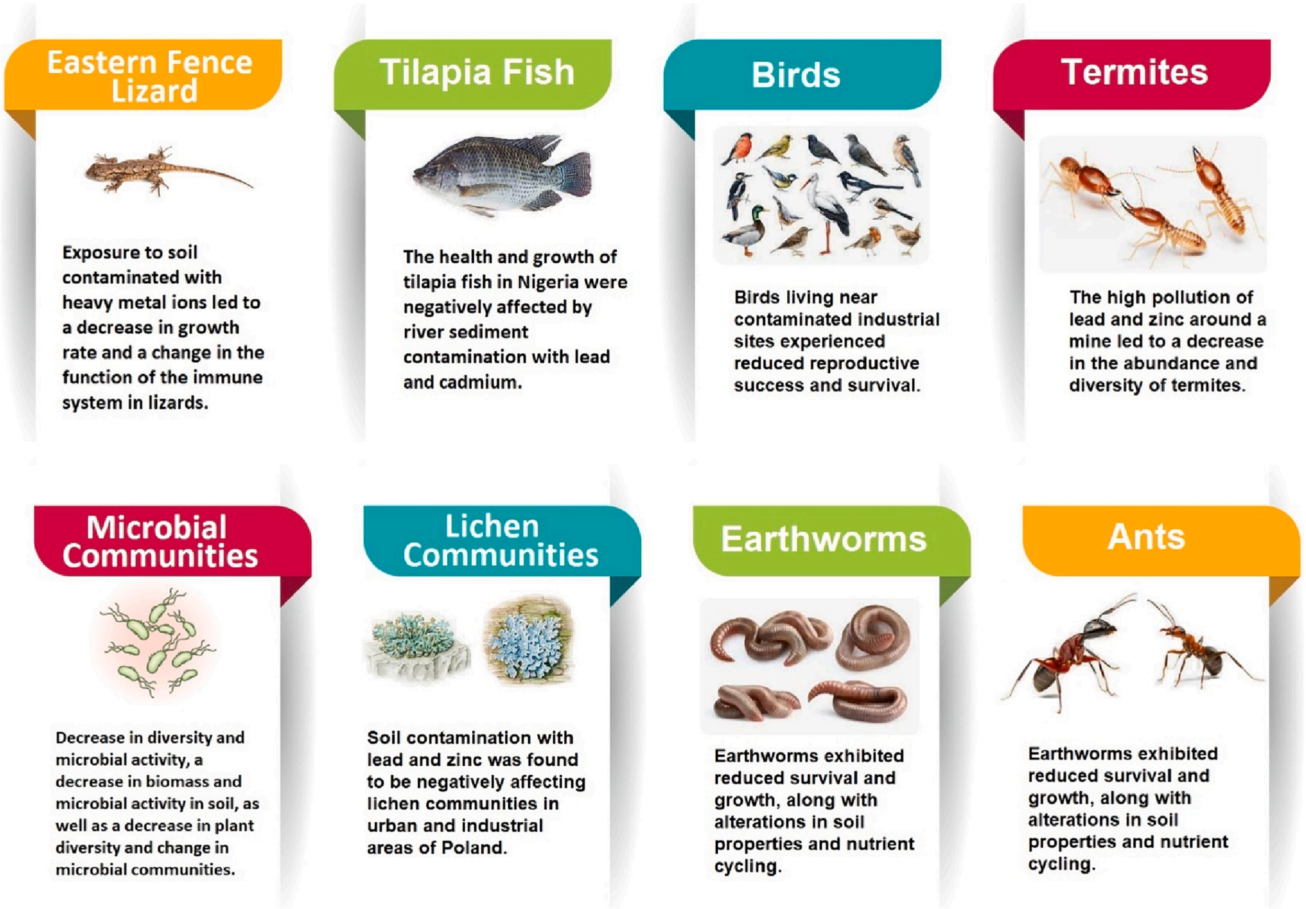

Fig. 3. Effects of Soil Contamination on Flora and Fauna Species: Eastern Fence Lizard (Brasfield et al., 2004), Tilapia Fish (Ahmed et al., 2023), Birds (Khan et al., 2023), Termites (Abadia et al., 2022), Microbial Communities (Pang et al., 2023), Lichen Communities (Rola et al., 2022), Earthworms (Li et al., 2023), Ants (Frizzi et al., 2017).

samples from significant and polluted points for each element separately, facilitating a more precise and detailed analysis (Neo et al., 2022).

Moving on to the analysis stage, the selection of appropriate techniques is of paramount importance. Atomic Absorption Spectroscopy (AAS) is employed for measuring the concentration of each element individually in soil samples, providing accurate information on the concentrations of lead, zinc, manganese, iron, and copper. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is utilized for the high-precision analysis of trace elements in soil samples (Ech-Charef et al., 2023). Fluorescence X-ray (XRF) is also used for simultaneous analysis of the concentrations of lead, zinc, manganese, iron, and copper in soil samples, offering rapid results (Qu et al., 2022).

AAS is suitable for measuring individual elements with high accuracy, but it may be less efficient for multielement analysis compared to ICP-MS. On the other hand, ICP-MS offers high sensitivity and multielement capability, making it ideal for analyzing trace elements in soil samples. The choice between AAS and ICP-MS depends on the specific analytical requirements of the study, such as detection limits, sample throughput, and available budget. AAS may be preferred for routine analysis of major elements, while ICP-MS is more suitable for trace element analysis. XRF provides rapid, non-destructive analysis of multiple elements in soil samples, making it suitable for high-throughput screening. It requires minimal sample preparation and can analyze large sample volumes quickly. Despite its advantages, XRF may suffer from lower precision and sensitivity compared to techniques like ICP-MS. It may also be less effective for detecting elements present at trace levels or for samples with complex matrices.

Furthermore, the application of Synchrotron-based X-ray Fluorescence Microscopy (XFM) allows for high-resolution imaging and a more detailed examination of the spatial distribution of lead, zinc, manganese, iron, and copper in soil samples (Masindi, 2017). Synchrotron-based XFM offers high spatial resolution and elemental mapping capabilities, allowing for detailed examination of the spatial distribution of heavy metals in soil samples. XFM requires access to synchrotron facilities, which may limit its availability and increase costs. It is also time-consuming and may not be suitable for routine analysis.

The Laser-Induced Breakdown Spectroscopy (LIBS) technique serves as a rapid and non-destructive method for assessing the concentrations of these elements in soil samples, providing continuous improvement in data collection from various points in the region (Zhang et al., 2021). It offers real-time elemental analysis and can be portable for field applications. LIBS may have lower sensitivity and accuracy compared to techniques like ICP-MS. It is best suited for qualitative or semi-quantitative analysis rather than precise quantification.

Table 6 provides a concise overview of various techniques for the detection and analysis of lead, zinc, manganese, iron, and copper in soil samples. These combined techniques form a comprehensive and precise approach to monitoring and evaluating contamination by lead, zinc, manganese, iron, and copper in soil. The resulting information is vital for making informed decisions aimed at improving the environment and safeguarding the health of both humans and other living organisms.

4.2. *Geographic information systems and remote sensing techniques*

Geographic Information Systems (GIS) and remote sensing

Table 6
Overview of Techniques for Heavy Metal Detection and Analysis in Soil.

Technique	Description	Advantages	Disadvantages	Reference
Magnetic Solid-Phase Extraction	Utilizes magnetic materials to selectively extract and concentrate target metals from soil samples for subsequent analysis.	Selective extraction, high sensitivity, and ability to pre-concentrate metals.	Limited to magnetic metals, may require optimization for different soil types, and potential interference from other magnetic substances.	(Xiao et al., 2023; Zhou et al., 2024)
Portable X-ray Fluorescence (PXRF)	Handheld devices that use X-ray fluorescence to determine the elemental composition of soil in real-time, providing quick on-site analysis.	Rapid, non-destructive, on-site analysis, and simultaneous detection of multiple elements.	Limited depth penetration, may require calibration for specific soil types, and potential interference from sample matrix.	(Kirichkov et al., 2024)
Sequential Extraction	A laboratory-based method that involves a series of chemical extractions to partition metals in soil into different phases, helping assess their mobility.	Provides information on metal speciation and mobility in the soil.	Time-consuming, requires specialized equipment, and may not represent in situ conditions accurately.	(Xu et al., 2023)
Laser-Induced Breakdown Spectroscopy (LIBS)	Utilizes laser-induced plasma to analyze the elemental composition of soil by measuring the emitted light spectrum.	Rapid, multi-element analysis, minimal sample preparation, and suitable for in situ and remote sensing applications.	Limited depth penetration, sensitivity to sample matrix variations, and potential for spectral interferences.	(Baruah et al., 2023; Ma et al., 2023; Zhao et al., 2022)
In situ Soil Analysis	On-site analysis methods that assess soil properties without the need for sample collection, providing immediate results for decision-making.	Real-time results, minimizes sample transportation, and facilitates rapid decision-making in the field.	Limited to surface analysis, may lack the precision of laboratory methods, and instrument costs may be high.	(Dou et al., 2024)
X-ray Fluorescence (XRF)	Non-destructive technique that uses X-rays to excite soil samples, producing fluorescent X-rays that are analyzed to determine elemental concentrations.	Non-destructive, rapid, multi-element analysis, and suitable for various soil types.	Limited sensitivity for certain elements, requires calibration, and potential interference from sample matrix components.	(Bilo et al., 2024)
Spectroscopic Techniques	Various methods (e.g., UV–Vis, IR) that analyze the interaction between soil and electromagnetic radiation to identify and quantify metal concentrations.	Wide applicability, non-destructive, and provides information on soil organic matter and mineral composition.	May require complex calibration models, sensitivity to soil moisture variations, and potential interference from other soil components.	(Zhang et al., 2023)
Electrochemical Techniques	Involves using electrodes and measuring electrical properties, such as voltammetry, to determine metal concentrations in soil.	High sensitivity, relatively low cost, and suitable for on-site measurements.	May require specific electrode materials, sensitivity to environmental conditions, and potential interference from other ions in the soil.	(Kumar et al., 2023)
Laser-Induced Breakdown Spectroscopy (LIBS)	As mentioned earlier, LIBS is a technique that uses laser-induced plasma for elemental analysis in soil samples.	Rapid, multi-element analysis, minimal sample preparation, and applicable to various sample matrices.	Limited depth penetration, sensitivity to sample matrix variations, and potential for spectral interferences.	(Yu et al., 2020)
Magnetic Susceptibility Measurements	Measures the soil's response to an applied magnetic field, providing information on magnetic minerals and potentially associated metals.	Non-destructive, rapid, and provides information on magnetic minerals in the soil.	May not directly measure metal concentrations, sensitivity to soil moisture content, and potential interference from non-magnetic minerals.	(Sudarningsih et al., 2023; Wang et al., 2023)

techniques are vital tools in the fields of mapping and monitoring spatial information. GIS, as a system based on spatial data, enables the collection, storage, analysis, and accurate visualization of spatial information (Yang et al., 2022). Utilizing spatial data such as maps and GPS information, GIS identifies patterns and spatial relationships through detailed analysis. Effective parameters in GIS and remote sensing techniques include spatial data, coordinate systems determining precise object locations in two or three dimensions, spatial analysis for in-depth analysis of spatial data to extract desired patterns and information, geographic databases providing a data structure for efficient storage of spatial information, image processing for analyzing satellite or aerial images to extract spatial information, spatial modeling using models and algorithms to simulate and predict spatial events and phenomena, and raster and vector maps presenting information through pixelated images or lines and points, respectively (Pfitzner et al., 2022). These parameters, in collaboration, create a comprehensive analytical environment in various fields such as urban planning and ecology. Table 7 provides a comprehensive comparison of Geographic Information Systems (GIS) and Remote Sensing methods for mapping and monitoring soils contaminated with heavy metal ions. Various studies across different locations worldwide employ these techniques to assess heavy metal pollution, identify contamination sources, and map spatial distributions. Strategic sampling point selection in the field of soil contamination possesses characteristics and advantages that can contribute to the improvement of assessment and monitoring of soil contamination, particularly heavy metal ions (Nwazelibe et al., 2023). In this approach, sampling points should have the ability to represent the credibility and reliability of the overall condition of the region, effectively visualizing macroscopic changes in pollution. Furthermore, these points should be distributed across various areas of the region, encompassing diverse and variable soil conditions to depict environmental diversity in the samples. Monitoring the pathways of heavy metal transport, temporal distribution of pollution, the impact of geographical variations, and awareness of potential pollution sources are also essential features in point selection (Khan et al., 2022b). Moreover, the number of sampling points should be sufficient to ensure the reliability of the information obtained from them. This selection should be satellite-based and conducted periodically to enhance pollution monitoring, improve the understanding of pollution dynamics, and observe changes in pollution over time.

5. Exploring physical, chemical, and biological remediation techniques

Remediating contaminated soil is a critical and significant issue with a substantial impact on preserving environmental health and ensuring food security for communities (Xie et al., 2021). Soil, as a fundamental component of the environment, plays a crucial role in maintaining biodiversity and the balance of ecosystems (Li et al., 2020). Remediating contaminated soil implies preserving and enhancing the quality of this valuable environmental component (Shukla et al., 2022). Soil serves as the primary growth medium for agricultural products. If the soil is contaminated, harmful elements may be absorbed by crops, posing health risks to consumers (Thatikayala et al., 2023). Soil remediation contributes to improving the quality of agricultural products and

Table 7
Comparison of GIS and Remote Sensing Methods for Mapping and Monitoring Soils Contaminated with Heavy Metal Ions.

Contaminant(s)	Location	Methodology	Results	Implications	Reference
Mapping and monitoring heavy metal pollution	China	Lead, Zinc, Manganese, Copper	Utilizing remote sensing and GIS	Implementation of unmanned aerial vehicles (UAV) for high-resolution imagery	(Yang et al., 2022)
Identification of sources of heavy metal contamination	Liberia	Lead, Manganese, Copper	Employing GIS analysis and statistical modeling	Integrating GIS data with soil and water quality data	(Koon et al., 2023)
Mapping heavy metal contamination in urban areas and engaging the community	Hungary	Manganese, Copper	Utilizing GIS analysis	Effective communication and community engagement with residents	(Horváth et al., 2018)
Mapping and monitoring of heavy metal contamination in agricultural soils	China	Lead, Zinc, Manganese, Copper	Leveraging remote sensing and GIS data	Integrating machine learning algorithms and Sentinel-2 satellite data	(Dai et al., 2022)
Mapping and monitoring of heavy metal contamination in industrial sites	Iran	Lead, Zinc, Manganese, Copper	Utilizing remote sensing and GIS data	Integrating spectral indices and machine learning algorithms	(Goodarzi et al., 2023)
Spatial prediction of soil heavy metal pollution	China	Lead, Zinc, Manganese, Copper	Applying machine learning algorithms and geostatistics	Integrating soil, geologic, and remote sensing data	(Chen et al., 2023)
Mapping of heavy metal pollution in agricultural soils	China	Lead, Zinc, Manganese, Copper	Utilizing machine learning and remote sensing data	Integrating multiple spectral indices and random forest algorithm	(Wang et al., 2023)
Developing an integrated approach for mapping heavy metal contamination	China	Lead, Cadmium, Zinc, Manganese, Copper	Utilizing remote sensing data and field surveys	Combining machine learning algorithms and GIS analysis	(Wang et al., 2023)
Assessing the spatial distribution of heavy metals in urban soil	China	Lead, Zinc, Copper	Utilizing remote sensing data and field surveys	Employing spatial interpolation and mapping techniques	(Deng et al., 2023)
Mapping the spatial extent of lead contamination in soils	USA	Lead	Utilizing aerial photographs and field samples	Applying object-based image analysis	(Miao et al., 2015)
Developing a decision support system for mapping heavy metal contamination	Iran	Lead, Cadmium, Nickel	Utilizing remote sensing data and field surveys	Employing GIS analysis and decision tree algorithms	(Azizi et al., 2022)
Mapping lead and zinc contaminated soils	Tunisia	Lead, Zinc	Utilizing remote sensing imagery and field measurements	Employing a random forest model and GIS analysis	(Mezned et al., 2022)
Identification of areas of heavy metal contamination	India	Lead, Zinc, Manganese, Copper	Utilizing Sentinel-2 satellite data and field measurements	Applying machine learning algorithms and GIS analysis	(Khan et al., 2022a)
Assessing the spatial distribution of heavy metal pollution	Nigeria	Lead, Zinc, Manganese, Copper	Utilizing remote sensing imagery and field measurements	Employing geostatistical analysis and GIS techniques	(Nwazelibe et al., 2023)
Identifying the sources of heavy metal pollution	Iran	Lead, Zinc, Manganese, Copper	Utilizing remote sensing imagery and field measurements	Applying spectral indices and machine learning algorithms	(Asadzadeh et al., 2020)
Identifying and mapping contaminated soils using spectral indices and machine learning	Turkey	Lead, Zinc, Manganese, Copper	Utilizing Sentinel-2 imagery and soil samples	Applying spectral indices and Support Vector Machine (SVM)	(Albayrak et al., 2021)
To map the distribution of lead, zinc, manganese, and copper in soil using remote sensing and GIS techniques	China	Lead, Zinc, Manganese, Copper	Utilizing Landsat 8 OLI, Sentinel-2A MSI	Employing a novel approach combining decision tree, random forest, and backpropagation neural network algorithms with spectral indices	(Wu et al., 2022)
To assess the suitability of different remote sensing techniques for mapping lead, zinc, manganese, and copper contamination in soil	UK	Lead, Zinc, Manganese, Copper	Utilizing hyperspectral imaging and Sentinel-2A MSI	Comparing two different remote sensing techniques for lead, zinc, manganese, and copper mapping using supervised classification and accuracy assessment	(Yingjie Li et al., 2021)
To investigate the use of drone-based hyperspectral imaging for mapping lead, zinc, manganese, and copper in soil	Australia	Lead, Zinc, Manganese, Copper	Utilizing drone-based hyperspectral imaging	Developing a novel classification method using support vector machine algorithm and feature selection techniques	(Pfitzner et al., 2022)
To develop a model for mapping and monitoring lead, zinc, manganese, and copper contamination in soil using machine learning algorithms	Morocco	Lead, Zinc, Manganese, Copper	Utilizing field data and Landsat-8 satellite imagery	Applying Random Forest algorithm and spectral indices	(Acharki, 2022)

ensuring food security (Pal et al., 2023). Soil unintentionally acts as a filter for water, reducing groundwater pollution. Contaminated soil, however, can allow harmful elements to infiltrate water sources, leading to a decline in water quality and associated health hazards (Song et al., 2017).

Contaminated soil can pose threats to the health of humans and other organisms. Soil remediation involves the elimination or reduction of various pollutants, such as heavy metals, organic materials, or chemicals, directly impacting human health and the environment. Soil serves as the foundation for production in the agricultural and industrial sectors (Faiza Amin et al., 2023). If the soil is contaminated, the performance of agricultural products diminishes, negatively affecting industries dependent on soil resources. Soil remediation contributes to environmental sustainability, helping to maintain a balance between the economy and the environment.

A comparative Table 8 of various techniques for addressing soil pollution indicates that electrodes are the optimal choice for soils with low permeability, albeit with high energy consumption and slow processes. Plant uptake offers a sustainable and cost-effective approach, although it is slow and dependent on plant growth conditions. Surfactant flushing is effective for surface contaminant removal but comes with high surfactant costs and the potential for groundwater pollution. Pump-and-treat systems are efficient for surface pollutant removal and adaptable to various situations but incur high costs and produce pollutant-contaminated waste. Electrical current has the capability to treat deep-seated pollutants with minimal soil disturbance and reusable electrodes, yet it consumes high energy and may generate acidic/alkaline waste.

In the realm of physical approaches, excavation refers to the removal of contaminated soil through digging or dredging, followed by on-site

Table 8
Comparative Analysis of Techniques for Soil Remediation.

Technique	Material	Advantages	Limitations	Reference
Electrodes	Citric Acid	Effective for low permeability soils; minimal soil disturbance	High energy usage; potential for metal redeposition; slow process	(Sotolářová et al., 2021; Zhu et al., 2024)
Plant Uptake	Sunflower; Vetiver Grass	Sustainable and low cost; can be used on-site; aesthetic value	Slow process; dependent on plant species and growth conditions; not effective for deep contamination	(Kriti et al., 2021)
Surfactant Flushing	Tween 80	Effective for removing surface contaminants; can be used on-site	High cost of surfactant; potential for groundwater contamination	(Priyadarshini and Chattopadhyay, 2023)
Pump-and-Treat System	Surfactants, Chelating Agents	Effective in removing surface contaminants; can be used in situ or ex situ	High cost; generates large amounts of contaminated waste	(Li et al., 2023)
Electrical Current	Electrodes, Electrolyte	Can treat deep-seated contaminants; minimal soil disturbance; reusable electrodes	High energy consumption; only applicable to low-permeability soils; may generate acidic/alkaline waste	(Subramaniam et al., 2024)
Magnetic Field	Magnetite	High efficiency; low cost; reusable material	Limited to surface contamination; requires pre-treatment of soil	(Amin et al., 2023)
Stabilization	Kaolinite, Lime	Effective for long-term immobilization of contaminants	High cost; may require multiple applications	(Dwivedi and Gupta, 2023)
Stabilization/Solidification	Cement, Fly Ash	Effective for reducing leachability of contaminants	High cost; may require significant soil disturbance	(Liu et al., 2024)
Incineration	–	High efficiency; reduces volume of contaminated soil	High cost; energy intensive; may release pollutants to air	(Bo et al., 2022)
Magnetic Field	Iron Oxide	High efficiency; low cost; reusable material	Limited to surface contamination; may require pre-treatment of soil	(Mahanty et al., 2023)
Stabilization	Biochar, Cement, Fly Ash	Effective for long-term immobilization of contaminants; can improve soil fertility	High cost; may require multiple applications; limited applicability to certain soil types	(Li and Wang, 2023)
Stabilization/Solidification	Cement, Fly Ash	Effective for reducing leachability of contaminants; can improve soil strength	High cost; may require significant soil disturbance; potential for secondary waste generation	(Fan et al., 2021)
Pyrolysis	–	High efficiency; reduces volume of contaminated soil; can recover energy and nutrients	High cost; energy intensive; potential for air pollution	(Yang et al., 2023)
Co-treatment with Phosphate and Calcined Oyster Shell	Phosphate and Calcined Oyster Shell	Low cost, eco-friendly, and easy to apply	Only effective in slightly acidic or neutral soil conditions	(Zhao et al., 2024)
In-situ Stabilization	Biochar and Lime	Low cost and eco-friendly	Lime may increase soil pH, potentially affecting soil properties and plant growth	(Wang et al., 2020)
Fenton-like Oxidation	Ferrous Sulfate and Hydrogen Peroxide	Effective in a wide range of soil conditions and removes both Pb and Zn	Generates large amounts of sludge and potential environmental risks associated with disposal	(Xing et al., 2024)
Sulfide Treatment	Sodium Sulfide	Low cost and eco-friendly	Generates H2S gas which is toxic and has an unpleasant odor	(Zhang et al., 2024)
Anion Exchange Resin	Macroporous Weak Base Anion Exchange Resin	High selectivity for lead and zinc	Requires frequent resin replacement	(Marszałek et al., 2023)
Fungal Remediation	Pleurotus Ostreatus	Effective in removing multiple contaminants	Limited field studies and requires further research	(Xu et al., 2021)
Microbial Augmentation	Micrococcus sp., Bacillus sp., and Pseudomonas sp.	Increases microbial activity and enhances remediation efficiency	Limited effectiveness in highly contaminated soils	(Cao et al., 2023; Yadav et al., 2023a)

treatment or transport to an appropriate disposal facility (Li et al., 2019). This method is typically effective in cases where the volume of contaminated soil is relatively low or contamination is limited to specific areas. Soil venting capitalizes on the natural process of volatilization, where contaminants transform into vapors that are expelled from the soil (Zhan et al., 2023). This method proves particularly efficient for volatile organic compounds (VOCs), especially when contaminants easily transition from liquid to vapor states (Shi et al., 2019). Soil washing, on the other hand, employs a treated solution to dissolve and separate contaminants from the soil, resulting in cleaner soil. This technique is highly effective for removing organic and heavy materials, especially when dealing with fine-grained soils (Li et al., 2019).

Chemical remediation comprises a diverse set of techniques that leverage chemical compounds to address soil contamination, aiming to immobilize, transform, or eliminate contaminants (Jou and Huang, 2003). The Soil Washing method is instrumental, involving the treatment of contaminated soil with a chemical solution (Lin et al., 2022; Yang et al., 2022). This solution acts as a solvent, effectively dissolving and separating organic compounds and heavy metals from the soil matrix. This process is particularly valuable in cases where targeted removal of specific contaminants, such as organic pollutants or heavy metals, is required.

Stabilization/Solidification, another chemical approach, employs the addition of specific chemical additives to the soil. These additives induce reactions that bind and immobilize contaminants, forming stable compounds. This technique is especially advantageous in impeding the mobility of heavy metals and organic substances within the soil, preventing their further spread or leaching into groundwater (Ma et al., 2019; Zhang et al., 2021).

Electrokinetic Remediation utilizes an electric current passed through the soil, leading contaminants to move towards electrodes, where they can be subsequently extracted. This method is highly effective in removing heavy metals and soluble contaminants, providing a targeted and controlled remediation approach (Zhu et al., 2024).

Each of these chemical remediation approaches offers a distinct set of advantages and applications, allowing for tailored strategies in addressing various soil contamination challenges. The selection of a specific technique depends on factors such as the type and extent of contamination, soil composition, and the desired remediation outcome. To mitigate pollution caused by heavy metal ions, including lead, zinc, manganese, iron, and copper, from contaminated soils, two biological approaches are employed to enhance soil quality and remove metal pollution: Phytoremediation involves the use of plants to absorb, accumulate, and detoxify heavy metals from the soil. Certain plant species, known as hyperaccumulators, have the ability to accumulate high concentrations of metals in their tissues without displaying toxic effects. These plants can be strategically cultivated in contaminated areas to uptake and sequester metals, thereby reducing soil contamination. Once the plants have absorbed the metals, they can be harvested and disposed of, effectively removing the contaminants from the soil (Huang et al., 2023). Bioremediation employs microorganisms such as bacteria, fungi, and algae to degrade or immobilize heavy metals in the soil. Microorganisms can transform soluble metal ions into insoluble forms or bind them to their cell surfaces, reducing their mobility and bioavailability. This process can be enhanced by optimizing environmental conditions, such as pH and nutrient levels, to promote the activity of metal-tolerant microorganisms (Fei et al., 2022).

The bioremediation process, through biostimulation and bioaugmentation, involves methods for degrading pollutants (Gupta et al., 2022). The former relies on native microorganisms, while the latter entails the injection of exogenous microorganisms with the contaminants. Significant progress has been made in pollutant degradation through bioremediation. It has been reported that lactic acid-producing bacteria such as Bifidobacterium longum, B. lactis, and Lactobacillus fermentum have the ability to remove two heavy metals, lead, and cadmium, from water. Description of bacteria and enzymes related to the degradation of polyethylene terephthalate exists. Due to the challenges associated with controlling the growth parameters of microorganisms, their use in bioremediation is limited (Bharagava et al., 2020). Metagenomics has emerged as an effective strategy in understanding efficacious microorganisms, functional genes, bioactive molecules, and enzymes in a particular sample of the environment. Both function-based and sequence-based approaches are effective in characterizing microorganisms and their gene products for an efficient degradation process. These products include enzymes such as oxygenases, peroxidases, xylanases, and oxidoreductases derived from microbial sources using genomic, metagenomic, and metatranscriptomic approaches. Rapid analysis of microbes and their associated products through *meta*-omics has revolutionized microbial studies (Wani et al., 2022).

Plant-based remediation methods, collectively known as phytoremediation, offer environmentally sustainable approaches to mitigate soil contamination (Dikšaitytė et al., 2023). Various plants, such as Brassica napus, Brassica juncea, Festuca arundinacea, Pinus massoniana, Phragmites australis, Medicago sativa, Lolium perenne, Robinia pseudoacacia, Indian mustard, Vetiver grass, Fern, Sedum alfredii, Chrysopogon zizanioides, and Helianthus annuus, are among the species utilized in phytoremediation processes for the removal of heavy metal ions (Steliga and Kluk, 2020; Yadav et al., 2023b). These plants, with their unique biological characteristics, play a significant role in absorbing, accumulating, and reducing the levels of heavy metals from soil and water (Li et al., 2021). These techniques harness the natural capabilities of plants to absorb, accumulate, and often transform pollutants, providing eco-friendly alternatives to traditional remediation practices (Yang et al., 2023).

This method encompasses various techniques tailored to different pollutants, including phytoextraction, phytostabilization, and phytovolatilization. Particularly, phytoextraction is a significant mechanism for removing heavy metals from contaminated areas, which can create economic benefits through phytomining (Bharagava et al., 2020). Factors influencing the efficiency of phytoextraction include the bioconcentration factor and translocation factor, which respectively indicate metal accumulation and translocation within plants. Enhancers such as chelators and soil amendments can enhance the efficiency of phytoextraction by increasing metal accessibility and reducing toxicity (Saxena et al., 2019).

Ramzan et al. (Ramzan et al., 2024) conducted a study on the tolerance and phytoremediation potential of Helianthus annuus, Zea mays, and Brassica juncea in heavy metal-contaminated soil sourced from the Lyari River. Their results indicated that all three experimental crops exhibited enhanced germination and growth in the contaminated soil compared to uncontaminated soil. Zea mays displayed superior resistance to heavy metal pollution, while sunflower and mustard demonstrated significant absorption of copper in their stems, suggesting high bioaccumulation factors. Moreover, maize and sunflower showed higher iron storage, while all cultivated species exhibited efficient rhizome storage with transfer factors less than 1. Overall, maize was identified as the most resistant plant to heavy metals, while sunflower was recognized as the best hyperaccumulator.

Lee et al. (Lee et al., 2023) investigated the long-term phytoremediation characteristics of Festuca arundinacea in diesel- and heavy metal-contaminated soil over a period of 571 days. They observed that tall fescue efficiently absorbed cadmium, with a bioconcentration factor of 0.58. The study also revealed distinct bacterial communities associated with petroleum hydrocarbon degradation and heavy metal tolerance. Furthermore, correlation analysis indicated that soil pH and organic content significantly influenced pollutant concentrations, while ambient temperature did not notably impact phytoremediation performance.

Rhizofiltration is a biological process used to purify surface water and groundwater through the use of plant roots. In this process, plants absorb and remove harmful substances in water using their roots; fertilizers and bacteria play a very important role in the rhizofiltration technique (Bakshe and Jugade, 2023). Waseem et al. (Waseem et al., 2024) explored the rhizofiltration potential of Helianthus annuus in industrially contaminated soils containing heavy metals. Their experiment included three concentrations of contaminated soil amended with compost, along with bacterial treatments. After sixty days, sunflower plants inoculated with Stutzerimonas stutzeri and Pseudomonas sundara exhibited increased plant height, biomass, pigment levels (including chlorophyll *a*, b, and carotenoids), and protein content. Additionally, there was a notable increase in antioxidant activity (e.g., catalase, peroxidase, ascorbate peroxidase) and a decrease in hydrogen peroxide content in plants inoculated with these bacteria. Moreover, the bacterial treatments facilitated the uptake of heavy metals (cadmium, chromium, and lead) by the sunflower plants. Liu et al. (Liu et al., 2024) investigated the impact of bio-organic fertilizer on enhancing phytoremediation efficiency of heavy metals-contaminated saline soil. They found that the application of bio-organic fertilizer resulted in a significant increase in biomass (from 150.87 % to 401.58 %) and improvement in the accumulation of heavy metals (from 87.50 % to 410.54 %) and salts (from 38.27 % to 271.04 %) in Medicago sativa. Khilji et al. (Khilji et al., 2024) utilized African marigold (Tagetes erecta L.) as a phytoremediator. In a pot experiment, marigold plants were grown in pots with three different concentrations (0 %, 5 %, and 10 %) of contaminated soil, supplemented with organic fertilizer (2 %) in all pots. Additionally, three types of bacteria, namely Co, Stutzerimonas stutzeri, and Pseudomonas sundara, were applied. After sixty days, the results showed that inoculation with Stutzerimonas stutzeri and Pseudomonas sundara increased the height and weight of African marigold plants compared to the control group. These bacteria also increased pigment levels, protein content, and water availability in the plants. Furthermore, the bacteria enhanced antioxidants such as melatonin, catalase, peroxidase, ascorbate peroxidase, and proline, reducing oxidative stress. Moreover, plants treated with Stutzerimonas stutzeri and Pseudomonas sundara absorbed higher concentrations of heavy metals (chromium, cadmium, and lead) in their various parts.

Recent studies in the field of phytoremediation have shown that the use of plants and bacteria can significantly improve the remediation of heavy metal-contaminated soils. In particular, plants such as maize and sunflower have been recognized as effective options for absorbing and removing heavy metals, while bacteria can accelerate the phytoremediation process. The use of enhancer methods such as organic fertilizers and bacterial inoculation enhances the plants' ability to absorb and remediate contaminants. These studies demonstrate that phytoremediation can be an effective solution for cleaning up heavy metal-contaminated environments and contributing to soil quality improvement and environmental preservation.

6. Innovative solutions for heavy metal ion pollution control

6.1. Innovative strategies for mining waste management

The management of mining waste and its rehabilitation are considered vital components of sustainable mining practices due to their significant environmental and economic impacts (Benkirane et al., 2023; Yin et al., 2024). Through proper management of mining waste, negative environmental effects such as air and water pollution and loss of biodiversity are minimized. Rehabilitation involves the recycling of materials, reducing the consumption of natural resources, and providing economic opportunities. These approaches are essential for preserving the environment and enhancing economic efficiency, forming the foundation for sustainable mining (Borden et al., 2022). Due to the complex chemical and physical composition of these wastes, the processes of their management, disposal, or recycling present inherent difficulties (Gauthier et al., 2021). Additionally, addressing the environmental impacts and extracting value from mining waste necessitates investments in advanced technologies and extensive research. The establishment of effective standards and regulations is also essential to ensure that mining waste management is conducted in a sustainable and value-added manner.

Khandani et al. (Khandani et al., 2023) addressed the possibility of using construction and demolition waste (CDW) materials in the mining industry for sustainable development. Through necessary experiments and analyses, the results demonstrated that by utilizing a mixture of recycled CDW materials and Portland cement, it is feasible to produce backfill materials with desirable mechanical and physical properties for mining applications. Among the strategies employed to enhance the characteristics of the backfill materials were the removal of detrimental components from the recycled materials such as gypsum, along with an increase in cement content in the mixture. These strategies not only contribute to improving the properties of backfill materials but also can be effective in promoting sustainable development in the mining industry by reducing the consumption of natural resources and waste generation.

Wang et al. (Wang et al., 2023) have addressed the critical issue of recycling and managing mine tailings for sustainable development in their review article. With a focus on Pb-Zn mine tailings, they investigated the utilization of municipal solid waste incineration fly ash (MSWIFA) and ground granulated blast-furnace slag (GGBFS) for solidification and stabilization, leading to the production of unfired bricks. Through their research, they demonstrated that this approach not only effectively immobilizes heavy metals present in the tailings but also produces bricks with satisfactory mechanical properties and environmental performance. By forming hydration products such as ettringite and portlandite, the bricks exhibit enhanced physical strength while meeting relevant regulatory limits for heavy metal leaching. Furthermore, the substitution of cement with MSWIFA and GGBFS in the stabilization process not only reduces energy consumption and greenhouse gas emissions but also offers economic benefits.

Huang et al. (Huang et al., 2024) present a zero-carbon processing method for stabilizing hazardous mine tailings (HMTs) using waste rice husk ashes (RHAs) and carbide slag (CS) in specific ratios, focusing on Pb-Zn tailings. The resulting solid materials exhibit good adhesive strength and mechanical properties, with reduced leaching toxicity concentrations of heavy metals Pb, Zn, Cr, and Cd. Transformation mechanisms involve the formation of C-S-H gels (Types I and II), cation hydroxides, and CO_2 mineralization. Cations are predominantly immobilized as residual compounds, with diffusion coefficients falling within acceptable ranges, ensuring effective stabilization against leaching.

Long et al. (Long et al., 2024) investigated the transformation behavior of heavy metals during the co-thermal treatment of hazardous waste incineration fly ash (HWIFA) and Fe-containing hazardous waste (including hazardous waste incineration bottom slag (HWIBS) and electroplating sludge (ES)). The study demonstrated that this treatment effectively reduced the static leaching toxicity of Cr and Pb. At temperatures exceeding 1000 °C, the co-thermal treated samples showed low concentrations of dynamically leached Cr, Pb, and Zn, indicating successful detoxification. Thermodynamic analyses and phase transformation results indicated that spinel formation and the gradual disappearance of chromium dioxide in the presence of Fe-containing hazardous wastes contributed to chromium solidification. Efficient detoxification of Pb and Zn was attributed to their volatilization and entry into the liquid phase during co-thermal treatment.

Li et al. (Li and Shimaoka, 2024) proposed an environmentally friendly process for recovering zinc (Zn) and copper (Cu) from municipal solid waste incineration (MSWI) fly ash through ammonium chloride leaching and ammonia removal. The leaching process selectively extracted Zn and Cu with impressive recovery rates of 54.39 % and 86.23 %, respectively. Subsequent ammonia removal from the leachate yielded recovery rates of 95.99 % for Zn and 98.90 % for Cu. The overall recovery rates of Zn and Cu from fly ash reached 52.21 % and 85.28 %, respectively. The recovered precipitate contained significant concentrations of Zn (33.62 %) and Cu (14.19 %), making it suitable for metal smelting. Additionally, the process led to a considerable reduction in fly ash mass and chlorine content, enhancing its potential for use in construction materials and cement production.

Zeng et al. (Zeng et al., 2024) successfully processed low-quality Pb-Zn oxide mine tailings at the Lanping mine using a carbon thermal reduction method based on the RHF furnace. This method effectively separates Zn and Pb from gangue materials and reduces sulfur fixation efficiency, mitigating SO_2 emissions. Through thermal analysis, it was observed that CaO facilitates the conversion of metal sulfides to oxides at temperatures above 1000 °C. Optimal conditions, including a temperature of 1250 °C, a reaction time of 30 min, and the addition of 20 % thermal coal in ambient air, achieved Zn and Pb evaporation rates exceeding 98 % and 96 %, respectively. The resulting ZnO dust, with a purity of 83 %, is suitable for subsequent hydrometallurgical extraction.

Hu et al. (Hu et al., 2024) developed a method for producing lightweight aggregates with enhanced CO_2 adsorption and mineralization capabilities by incorporating multi-source industrial solid waste and porous materials. The study investigated the effectiveness of utilizing fly ash, desulfurization gypsum, coal gangue, blast furnace slag, and steel slag to enhance the performance of aggregates. Results indicated a 20 % reduction in water absorption rate and a 49.1 % increase in mechanical strength with the incorporation of these mining wastes. Throughout the carbonization curing process, CO_2 absorption consistently exceeded 20 %, attributed to the synergistic effects of the solid waste, which improved physical properties such as bulk density and mechanical strength. Addition of porous materials such as diatomite and zeolite further augmented porosity and enhanced CO_2 absorption to 26.3 %.

Tang et al. (Tang and Steenari, 2016) focused on developing sustainable mining practices. They conducted a comprehensive review aiming to optimize the leaching process of municipal solid waste incineration (MSWI) ash for resource recovery, with a particular focus on Cu, Zn, Pb, and Cd. Their study explored various leaching agents and parameters, such as acid type, pH, temperature, time, and liquid-to-solid ratio. Results indicated that hydrochloric acid was particularly effective for extracting Cu and Zn, with high yields achieved within 24 h at controlled pH levels. Additionally, efficient removal of hazardous metals like Pb and Cd was observed. However, leaching of bottom ash proved challenging due to gel formation, highlighting the need for alternative methods for metal recovery from this fraction. This research contributes to advancing sustainable mining practices by exploring innovative solutions for metal recovery from waste materials, thereby reducing environmental impact and promoting resource conservation.

Xu et al. (Xu et al., 2024) focused on sustainable mining development by addressing the challenges posed by metallurgical solid wastes. Through their review article, they highlighted the application of the coal-based direct reduction-magnetic separation (CBDRMS) process for recycling high-iron-content non-ferrous metallurgical wastes. By optimizing this method, they aimed to extract valuable resources from these wastes, mitigating environmental risks associated with disposal and contributing to resource conservation. Their research underscores the importance of innovative approaches in waste management to foster a circular economy within the metallurgical sector.

These research findings collectively underscore the importance of innovative strategies for sustainable mining waste management, emphasizing resource recovery, environmental performance, and the transition towards a circular economy within the mining industry.

6.2. Green chemistry and sustainable practices in the mining industry

Green chemistry and sustainable approaches in the mining industry have gained increased significance due to their crucial role in environmental preservation and responsiveness to the global community's need for sustainable resource utilization (Bilo et al., 2024). Green chemistry serves as a technological and environmental paradigm in the production of chemical materials, emphasizing reduced energy consumption in its processes and the use of recycled or renewable raw materials (Cameron et al., 2021). In mining, these approaches signify pollution reduction, process optimization, and energy consumption reduction. The adoption of sustainable technologies, such as the bio-based extraction of metals from low-grade materials or the utilization of renewable energy in mining processes, not only mitigates the environmental impacts of mining but also contributes to resource efficiency (Zhang et al., 2023). These transformations not only contribute to environmental conservation but also enable the mining industry to address challenges arising from resource constraints, positioning itself as a sustainable and responsible branch meeting the needs of society.

By implementing various measures, sustainable approaches in the mining industry play a fundamental role in reducing environmental impacts and optimizing operations (Valenzuela-Elgueta et al., 2021). These measures include utilizing biotechnologies for metal extraction or pollutant removal, implementing smart waste management through intelligent systems, relying on renewable energy sources, improving energy efficiency in mining processes, effective use of water resources, developing recycling technologies, and managing the safety and sustainability of mine waste (Zhu et al., 2012). These actions not only contribute to improving environmental conditions but also contribute to establishing more sustainable structures in the mining industry and addressing the needs of society (Guo et al., 2022). The use of biotechnologies, smart waste organization, emphasis on renewable energy, and attention to water resource efficiency are highlighted aspects of these approaches. These initiatives move towards a more sustainable and environmentally friendly mining community while aiding in increased efficiency and economic benefits (Brown et al., 2023).

Mining operations employ various measures with the aim of enhancing energy efficiency and mitigating environmental impacts. These initiatives encompass the utilization of smart mining technologies equipped with sensors for precise data collection, contributing to the optimization of energy consumption and mining processes. Additionally, the incorporation of intelligent and automated machinery, enhanced with artificial intelligence and automation technologies, ensures more energy-efficient operations (Song et al., 2023). Optimizing processes and equipment further results in a significant reduction in energy consumption within mining operations. The adoption of renewable energy sources, such as solar or wind energy, plays a crucial role in increasing sustainability and minimizing environmental effects in the mining industry (Cabello, 2021). Concurrently, the recycling and reuse of energy, process and equipment improvements, and the integration of sustainable technologies are key actions taken to enhance energy efficiency and reduce environmental impacts in mining operations.

To implement innovative approaches widely in the mining industry, various initiatives can be undertaken. Establishing robust research and development (R&D) departments with the aim of inventing new technologies in areas such as waste management, energy efficiency, and mineral extraction is a primary priority. Encouraging collaboration among different entities, including government, industry, universities, and research institutions, fosters the sharing of successful experiences and insights within the mining sector (Tang et al., 2023). Creating financial facilities with favorable conditions and promoting awareness within the industry about the significance and benefits of innovative approaches are also key measures. To successfully execute these approaches, formulating standards and regulations based on safety, environmental protection, and economic sustainability is essential. Furthermore, training employees and enhancing their motivation to actively participate in innovative projects are effective actions in this regard (Zhang and Schippers, 2022). Leveraging social networks for the exchange of information and experiences can facilitate collaboration among industry stakeholders and improve the process of implementing innovative approaches in the mining sector (Halinen et al., 2012).

6.3. Use of artificial intelligence (AI)

The integration of artificial intelligence (AI) in addressing lead and zinc soil contamination around mines can bring about significant improvements in monitoring and remediation efforts. The outlined approaches demonstrate how AI technologies can enhance various aspects of pollution control:

Predictive Modeling: AI can leverage predictive modeling to analyze a multitude of factors, including geological characteristics, mining activities, and weather conditions. By doing so, it can predict the likelihood of soil contamination in different areas around mines. These predictive models enable the identification of high-risk zones, allowing for more focused and efficient allocation of resources for monitoring and remediation (Gautam et al., 2023).

Monitoring: AI-powered sensors and drones can provide real-time data on soil quality. These technologies can cover large areas quickly and efficiently, offering a comprehensive overview of the soil conditions. Machine learning algorithms can then analyze the collected data, identifying patterns associated with pollution. This allows for early detection and timely intervention to prevent the escalation of soil contamination (Wang et al., 2019).

Optimization of Remediation Efforts: AI can contribute to the optimization of remediation strategies by analyzing extensive datasets related to soil characteristics and the effectiveness of various remediation methods. Machine learning algorithms can determine the most suitable and efficient remediation approach for a specific site, considering factors such as soil composition, topography, and the success rates of different methods in similar conditions (Peng et al., 2023).

Cost-Effective Solutions: The targeted and data-driven approach facilitated by AI can lead to more cost-effective solutions. By focusing resources on areas identified as high-risk and tailoring remediation strategies to specific site conditions, the overall efficiency of pollution control efforts is improved. AI's ability to analyze large datasets quickly and accurately also contributes to cost savings compared to traditional manual methods (Ji et al., 2022).

Building and implementing artificial intelligence (AI) systems involves a variety of software tools, frameworks, and libraries. The specific tools required can vary depending on the task, domain, and programming language preferences. Some key categories of software tools commonly used in AI development include programming languages such as Python (widely used for its simplicity and extensive libraries like NumPy, pandas, TensorFlow, and PyTorch) and R (commonly used for statistical analysis and machine learning). In the realm of AI frameworks and libraries, TensorFlow, developed by Google, stands out as an open-source machine learning framework, alongside PyTorch, an open-source library by Facebook known for its dynamic computational graph. Keras is often utilized as a high-level neural networks API that runs on top of TensorFlow or other backend engines, while Scikit-learn serves as a machine learning library for classical algorithms like regression, classification, and clustering (Ji et al., 2023; Pouyanfar et al., 2022).

Deep learning tools like CUDA and cuDNN provide GPU-accelerated computing for deep neural networks, and MXNet is a flexible and efficient deep learning library supporting multiple programming languages. For data processing and analysis, essential libraries include NumPy and pandas in Python, while Apache Spark proves useful for distributed data processing. Natural Language Processing (NLP) tools, such as NLTK and spaCy, cater to tasks involving human language data. Computer vision tasks are supported by OpenCV, a comprehensive library offering tools for image and video processing (Bhagat et al., 2022).

Version control is a system that manages changes made to files and code over time, allowing tracking and reverting to previous versions. Version control is ensured through Git, which is essential for tracking changes in code and facilitating collaboration. Popular integrated development environments (IDEs) like Jupyter Notebooks, PyCharm, VSCode, or Atom are utilized for interactive computing and Python development (Bhagat et al., 2022). Cloud platforms such as AWS, Azure, and Google Cloud provide infrastructure and services for training and deploying AI models. Containerization is a technology that packages software code and its dependencies into a standardized unit called a container to simplify and make software execution more portable. Containerization is made possible by Docker, enabling the creation and deployment of containerized applications, while Kubernetes orchestrates containerized applications, providing scalability and automation. These tools collectively support various stages of AI development, spanning data preprocessing, model training, deployment, and monitoring, with the choice of tools depending on the specific requirements and preferences of the development team.

7. Conclusion and future directions

The mining industry plays a crucial role in soil contamination with ions of lead, zinc, manganese, iron, and copper. Mining activities, product processing, waste management, and atmospheric deposits are the primary sources of contamination. These pollutants have extensive effects on soil, water, plants, wildlife, and human health. To address this issue, effective monitoring and assessment are essential to comprehend the precise dimensions of the problem and present necessary strategies for reduction and remediation. While traditional soil purification methods, such as physical, chemical, and biological approaches, have limitations, the utilization of emerging technologies and approaches is imperative for pollution control. The mining industry is progressively embracing green chemistry and sustainable practices to diminish environmental impacts and enhance efforts in addressing the issue. In general, managing pollution with ions of lead, zinc, manganese, iron, and copper is vital for preserving both human health and the environment.

The political and legal implications of this matter are significant due to the widespread effects of pollution with ions of lead, zinc, manganese, iron, and copper near mining areas. Governments and regulatory bodies must implement and enforce stricter environmental standards and more effective regulations to prevent pollution from mining activities. This includes enhancing waste management methods, employing gas control technologies, and establishing more efficient mechanisms for monitoring and enforcement. Furthermore, increased financial support for research into innovative techniques and methods for pollution control and remediation is necessary.

Future research should focus on the development of innovative technologies for mitigating and remediating pollution with ions of lead, zinc, manganese, iron, and copper. This involves the application of artificial intelligence and machine learning for predictive modeling and risk assessment, as well as advancements in more sustainable and environmentally friendly mining practices. Further research is needed to understand the long-term health effects of exposure to these ions, especially in vulnerable populations such as children and pregnant women. Finally, research is necessary to evaluate the effectiveness and feasibility of various pollution control and remediation strategies in different environmental and socioeconomic contexts.

CRediT authorship contribution statement

Atoosa Haghighizadeh: Data curation, Methodology. **Omid Rajabi:** Data curation, Software. **Arman Nezarat:** Data curation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Zahra Hajyani:** Data curation, Funding acquisition, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Mina Haghmohammadi:** Conceptualization, Data curation, Software, Validation, Writing – original draft, Writing – review & editing. **Soheila Hedayatikhah:** Conceptualization, Data curation, Resources. **Soheila Delnabi Asl:** Conceptualization, Data curation, Resources, Software, Writing – original draft, Writing – review & editing. **Ali Aghababai Beni:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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.

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