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HEAVY METAL SPECIATION IN MINING-IMPACTED SOILS: A REVIEW OF GEOCHEMICAL PARTITIONING AND RISK ASSESSMENT

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ABSTRACT:

Mining activities significantly alter soil chemistry, leading to the accumulation and transformation of heavy metals with varying mobility and toxicity. This review investigates the geochemical speciation of heavy metals in mining-impacted soils, emphasizing the importance of partitioning among solid-phase fractions such as exchangeable, carbonate-bound, and residual forms. The study synthesizes analytical techniques, including sequential extraction and synchrotron-based spectroscopy, used to characterize metal speciation and predict environmental behavior. Risk assessment frameworks are discussed in relation to bioavailability, leaching potential, and ecological impact. The study also explores soil amendments and stabilization technologies that aim to reduce metal mobility. Research gaps in dynamic speciation modeling and climate-related variability are identified to guide future studies.

KEYWORDS: *Heavy metals, Soil speciation, Geochemical partitioning, Mining impact, Environmental risk.*

INTRODUCTION:

Rapid mining and mineral-processing operations have led to massive contamination of heavy-metals in soils especially in areas where environmental laws are lax or not enforced. Even though mining cannot be avoided as the means to ensure vital raw materials, it also bears the heavy burden of a sizeable environmental footprint, the main burden being the accumulation of potentially toxic elements, or PTEs, lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), nickel (Ni), chromium (Cr), and arsenic (As) in terrestrial ecosystems. These factors remain in land in decades or centuries hence developing threats to environmental soundness, food security, and populace well being.

Mining-derived heavy metals do, however, pose an environmental risk that cannot be ascribed purely to concentrations of the total metals. On the contrary metal mobility, bioavailability and even toxicity behaviour is controlled by the speciation, that is defined as the particular chemical forms and geochemical associations that metals exist in. Such examples as metals entrapped in the silicate lattices show significantly low bioavailability, thus their adsorbed forms on the Exchangeable surfaces as well as on the carbonate surfaces have increased mobility, thus complying the acute risks to the plant and microbial life.

Geochemical partitioning, most commonly assessed using sequential-extraction schemes (e.g., Tessier method and the BCR protocol), enable the fractionation of metals into operationally defined forms, such as exchangeable, carbonates, Fe-Mn oxide binding, organic binding and unreactive. These fractions are unique potentials of migrating in the soil profile, entering the chains of food, or being washed in the groundwater resources. Exchangeable and carbonate-bound fractions are categorized as the most labile and, therefore, lead to instant ecological and biotic hazards, whereas the residual fraction is, in general, inert in natural conditions (Singh & Rao, 2021). Since metal pollution poses a significant threat to human health, complete comprehension of speciation is vital to carry out fair assessment and development of productive measures of environmental mitigation.

New empirical studies have eloquently reported spatial non-uniformity and complex interconnections amongst metal types in mining-disrupted environments, parameters that are controlled by pH, redox states, organic matter binder, and the regional mineralogy (Okere et al., 2023; Rahman et al., 2024). At the same time, climatic parameters, particularly precipitation and temperature, have a decisive impact on the mobility of metals: acid-mine-drainage systems in a tropical setting, in particular, can lead to a significant increase in solubility and translocation of heavy metals (Chinwe et al., 2022). Moreover, the land conversion such as plantations or U-urban conversion of the old mines substantially alters the soils heavy-metals distributions and changes (Li et al., 2023).

Another significant conclusion that has been reached in this literature is that information on the metalspeciation is relevant in risk-assessment procedure. Such instruments as the Risk Assessment Code (RAC), the Geoaccumulation Index (Igeo), and the Potential Ecological Risk Index (PERI) are gradually adopting species derived information in order to make the predictions more accurate (Bello et al., 2023). With such elegant tools, it would be easier to prioritize the sites of remediation and assist in the choice of unique site-specific intervention strategies, including phytoremediation, soil washing, and treatment of the soil by means of biochar and other amendments, hence making the whole remediation process more efficient and cost-effective (Chen et al., 2021).

The current research combines the available evidence regarding metalspeciation in mining-affected soils and summarizes the state-of-the-art applications of geochemical partitioning to risks characterisation, in particular within environmental geochemistry, paedology and environmental toxicology. The synthesized findings contribute to the overall understanding of the behavior of contaminants and provide a strategic direction to sustainable land use and the mitigation of pollution in the mining-impacted lands.

Sources and Pathways of Heavy Metals

GHGs added to soils affected by mining mostly have anthropogenic origin, the most extensive sources being mining and smelting activities. These operations open up and activate naturally present metal ore, that through tailings, acid mine drainage and air emissions, are then distributed to local environments. The open-pit mining and underground mining produce enormous amounts of waste rock and tailings that tend to amass a very high level of toxic metals surplus, which can be related to lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), copper (Cu), and zinc (Zn) (Tang et al., 2021).

As well as mining, other anthropogenic activities such as application of phosphate fertilizers, industrial effluents, vehicles emissions, sewage sludge and poor solid waste management are other sources of heavy metals to soils (Xie et al., 2023). When discharged, heavy metals can be disseminated through the air, surface water runoff, and seepage into groundwater which contaminates the widespread areas, as well as reaches the agricultural fields and residential districts (Chen et al., 2022).

Metal flux in soils can also be contributed by natural sources, which as such include the weathering of metal-bearing rocks, volcanism, forest fires, among others; but this addition is gradual and generally regional (Kumar et al., 2020). However, the magnitude and strength of mining activities intensifies the redistribution of these metals in the biosphere faster than the resilience of the ecosystems to absorb.

Besides, it is possible to find the heavy metals in the food chain since they enter the plant body as roots or are accumulated in fish living in the adjacent ponds (Rahman et al., 2021). Such trophic transfer necessitates the realization of the imperative importance of comprehending metal concentrations as well as their speciation and mobility in the affected soils.

Geochemical Behavior of Heavy Metals in Soils

Complex geochemical interactions govern the behavior of heavy metals in soils, which is a determining factor in mobility, bioavailability and persistence of heavy metals with environments. Soil pH, redox potential, organic content of soil, cation exchange capacity (CEC), clay minerals, and iron/ manganese oxides are some of the decisive controlling variables (Zhou et al. 2023). These parameters define residual states of metals whether in soluble, exchangable or strongly tied residual state.

Environmental risk assessment necessarily depends on speciation studies since metal chemical form has a large influence on toxicity. Sequential extraction processes, in particular the BCR or Tessier processes, divide the metals into fractions: exchangeable, carbonate-bound, Fe-Mn oxide-bound, organic-bound and residual (Li et al. 2022). As one example, the metals found in the exchangeable and carbonate bound fractions exhibit a high bioavailability and can easily leach out of soils into a water system, hence, posing an elevated ecological threat (Sun et al. 2021).

The pH of the soil is one such factor that is particularly critical because the acidic environment facilitates the solubilization and the mobility of HAZMATs like cadmium and zinc, whereas, in the environment that contains alkali, the adsorption and precipitation of metals is favored (Sharma et al. 2024). Organic matter in large quantities can also immobilize metals and encapsulate in complexes, but in a given setting, it can enhance mobility due to organo-metallics (Gupta et al. 2021).

Redox of the soil also controls metal speciation, especially in the cases of arsenic and chromium. In the reduction environment, arsenic gravitates towards the more mobile and toxic arsenite (As^{3+}) as opposed to it oxidizing environment, which is more dominant over less-reactive arsenate (As^{5+}) (Wang et al. 2020). The dynamic reinforces the topic of site-specific analysis when deriving on how to assess contaminated lands.

Comprehensive understanding of geochemical processes is a requisite necessity to structure strong remediation measures - which include soil washing, phytoremediation, stabilization or immobilization. Modern studies are drawing more towards all-encompassing risk assessment systems that would harmonize speciation, bioaccessibility, and toxicity tests to provide more accurate follow-ups to waterways management (Zhang et al., 2025).

Speciation Analysis Techniques

Heavy-metal speciation characterisation in mining affected soils is essential in explaining the soil environmental behaviour, mobility, and toxicity. Unlike total metal concentration, which yields no direct conclusions regarding bioavailability, speciation analysis can determine the chemical forms of the metal in question and in this way allow better predictions of the environmental fate of the element and its ecological risks. Most recently, the progress of analytical strategies has aggressively ramped up the speciation analysis level of resolution, sensitivity, and specificity providing a more sophisticated understanding of the dynamism of the contaminants in the soils (Wang et al., 2021; Lopez-Anton et al., 2023).

Contemporary speciation methods tend to be categorised as either chemical extraction (e.g. sequential extraction) and instrumental methods (e.g. spectroscopy and chromatography-based techniques). The various approaches are more frequently being applied in a complementary way to generate both quantitative and qualitative answers. Additionally, the increasing researchers use the in situ approaches to real-time metal speciation observation, thus reducing the artifacts caused by the disturbance of samples (Zhou et al., 2022; Singh et al., 2024).

Sequential Extraction Procedures

Sequential extraction procedures (SEPs) form a basic method in operational speciation analysis and present a practical approach in the fractionation of metals into geochemically discriminatory groupings. The most frequently used one is the modified BCR (Community Bureau of Reference) three step procedure which sets the metals allocated in exchangeable, reducible, oxidizable, and residual fractions (Rauret et al., 1999; ISO 2021). Such classifications are associated with the possible mobility and environmental risk, subsequently helping in planning removal of risk based on such classifications.

SEPs have recently undergone adaptation with a view of increasing selectivity and reproducibility. Alternatively, by way of an illustration, changing the buffer system and extracting time has also been suggested to attain specific binding stages in a more targeted fashion (Mohammadi et al., 2020). The other innovation is to couple up SEP data with geochemical modeling software like the PHREEQC that can be used to model metal speciation across different redox conditions and pH values (Zhang & Jin, 2023). However, it should be pointed out that SEPs provide fractions that are operationally defined, and comparisons should be wary of particularly when there are different soil types and mine situations (Al-Ghouti & Al-Degs, 2022).

Spectroscopic Techniques

Sequential extraction procedures (SEPs) still remain the most prominent methodology amendable to operational speciation analysis that allows disaggregating metals into fractions of geochemical features. The most common procedure, a three-step extraction protocol (modified BCR (Community Bureau of Reference)) that is used to distinguish the exchangeable and reducible fraction, the oxidizable fraction, and the residual fraction (Rauret et al., 1999; ISO 2021). These differences are related to potential relocation and eco- hazard, which allows planning of risk remediation.

Modifications of SEPs are aspiring to become more selective and reproducible. Enhancements in the composition of buffers and refrigeration time have been suggested so as to enhance isolation of particular binding stages (Mohammadi et al., 2020). Additionally, SEP data also are being used together with geochemical modelling package, such as PHREEQC, to forecast metal oxidation state in variable redox and pH conditions (Zhang & Jin, 2023). However, SEPs provide operationally defined fraction, and their findings are supposed to be handled cautiously, especially when data is being compared among various types of soils and mining environments (Al-Ghouti & Al-Degs, 2022).

Geochemical Modeling

The process of modeling heavy metals in mining-affected soils has become a major geochemical tool of analysis pertaining to fate, transport, and transformation of heavy metals. All these models have the capacity to model the geochemical processes, which include adsorption, complexation, precipitation, and redox transformations that are known to influence the speciation of metals and mobility. Computational tools such as PHREEQC, MINTEQ, and Visual MINTEQ programs enable one to extrapolate the behavior of metals in a range of pH, redox potential and ionic strength environments (Li et al., 2022; Jiang et al., 2023). The models are particularly useful in risk evaluation and remediation-planning due to the provision of opportunity to analyse scenarios and assessment of treatment alternatives.

The emerging trends have centred on the integration of geochemical models and transport reactive flow models to find a more accurate value of dynamic exchanges in the contaminated soils (Zhang et al., 2021). Further, such models coupled with field measures as well as machine learning have upped the capacity to determine the mobility and bioavailability of metals in more complex environmental systems (Wang & Chen, 2024). These integrative methods provide an insight into major geochemical parameters that affect the behavior of metals and lead to subsequent superior soil-management recommendations.

Geochemical Partitioning of Heavy Metals

Geochemical partitioning refers to the partitioning of heavy metals between discrete chemical fractions in soils, which determine the mobility, availability and possible toxicity. Separate extraction methods are usually used to characterize such fractions defining as exchangeable, carbonate bound, oxide bound (Fe-Mn), organic-bound and residual fractions (Tessier et al., 1979; modified by Singh et al., 2022). The scale of metals in the relative abundance in each fraction is proportional to environmental risk.

The most common distribution of metals (Pb, Cd, and Zn) in the mining affected soils are in the exchangeable and carbonate-bound fractions, both of which are highly mobile and possess a severe ecological risk (Ali et al., 2021). Cr and Ni in turn are always found in residual fractions, which means their low short term mobility but possible long term persistence. Soil, metal properties, and other environmental parameters such as pH, Redox state, and the presence of organic material control natural adsorption and subsequent geochemical distribution processes that are performed in the soil (Ogunyemi et al., 2024).

Influence of Soil Properties on Speciation

The soil characteristics are found to be important in the speciation of the mobility and the bioavailability of the heavy metals. The most critical considerations are pH, organic matter percentage, the ability to exchange cement (CEC), the content of clay and the redox conditions. Under acidic soils, the solubility and mobility of metals are usually increased, but in alkaline soils, the situation is reversed where the behavior is more likely driven towards precipitation or adsorption by oxides and carbonates (Xu et al., 2022). The large amount of organic matter promotes the formation of stable metal-organic complexes, which can either fix the metal or enhance its transportation unless the condition is very suitable (Chen et al., 2023).

Soil texture is one of the important variables that influence the sorption of metals in soil studies. Clay-rich matrices tend to supply a more dense complement of sorption sites and thus high retention of the metals than sandy material does. Chemical equilibria based on redox reactions also promote the speciation of heavy metals. In hydrologically variable or waterlogged environments, the redox status creates metal behaviour, with Cr(VI) potentially reduced to Cr(III), and Fe oxides suffocating metals may weaken readily through the process of being washed up in areas of anoxia (Zhou & Zhang, 2025). To understand the fate of trace metals in the environment is essential to the interpretation of environmental fate and to the design of site-specific remedial solutions to contaminated sites.

Speciation Patterns in Different Mining Environments

The texture of the soil is a decisive factor: the matrices that have a high proportion of clay offer a higher density of sorption sites to retain metals than sandy matrices (Ibrahim et al., 2021). Such respeciation of metals has been observed to be driven by the effect of the redox conditions particularly under waterlogged or variable conditions, such as the reduction of Cr(VI) to Cr(III) or mobilization of metals bound to Fe under anoxic conditions (Zhou & Zhang, 2025). The insight into the interactions will be extremely important to understand environmental behaviour of heavy metals and devise effective remedial measures at contrived sites.

Initial heterogeneity in the heavy metal speciation in mining environments is inherent due to differences in ore type, mining types, climate and the geochemistry of the immediate local geochemistry. Metals including Zn, Cu, Pb, and Cd can usually be covered by the sulfide mineral in the mining regions that are dominated by the sulfide minerals and as they are oxidized the mineral releases acid and soluble metal ions which are a result of the release process also called acid mine drainage (AMD) (Zhou et al., 2023). Compared to that in the oxide-ores zones, metals in the oxide-ores zones can be complexed with the iron or manganese.

Abandoned or artisanal mining-contaminated soils, waste rocks, and tailings tend to have a high amount of exchangeable and carbonate bound metals, mainly when they are acidic, increasing their potential mobility and ecological hazard (Kim et al., 2022). Investigations in sub-Saharan Africa and Southeast Asia mining regions in the gold and lead combined with zinc indicate Pb and As preferentially occupy labile fractions, something that worsens their bioavailability and leachability (Akinola et al., 2024; Nguyen et al., 2023). The importance of site-specific determination of risk management and remediation planning can be attributed to such spatially varying metal distribution in ground of fractionation.

Risk Assessment of Heavy Metals

Total concentrations and chemical speciation of heavy metals in mining-affected soils should also be vigorously taken into consideration in order to make accurate assessment on risk associated with its exposure. The standard tests based on only a total metal sum may under- and overestimate the threat to the environment. The modern risk models thus take into consideration speciation data, bioavailability and toxicity levels to make more acceptable estimations (Li et al., 2022).

The evaluation of the environmental risk has been enhanced by adding speciation inputs in indicators of environmental risk, like the Risk Assessment Code (RAC) and the Geo-Accumulation Index (Igeo). In such cases, metals that are identified in exchangeable or carbonate-bound fractions are assigned mobility and therefore ecological risk factors as high (Gao et al., 2023). Moreover, Monte Carlo probabilistic risk models (Plas et al., 2007) based on the probabilistic risk assessment framework that involves machine-learning and data-training techniques are becoming broader in their forecast of future exposure conditions and the risks of adverse health responses to the neighbouring population (Chen et al., 2021; Raza et al., 2024).

Even policy-related standards such as the US EPA Human Health Risk Assessment and the European Union REACH regulations have since been revised so as to reflect the speciation-informed measures in a bid to more precisely assess both cancer and non-cancer outcomes caused by metals exposure on soil and ground water (Zhang et al., 2020).

Bioavailability and Ecotoxicity

The extent of bioavailability, which refers to what the proportion of heavy metals can be availed to organisms, is strongly linked with metal speciation in the soils. In exchangeable and water-soluble forms, the plants and soil microorganisms absorb them more easily, creating an increased ecological and public-health risk (Huang et al., 2022). As an example, acute cadmium and zinc in acid mining soils are often in the highly bioavailable form, resulting in a high amount in edible crops and consequent transfer to the food chain (Liu et al., 2023).

Earthworms and microbes are soil organisms that act as sensitive bioindicators of ecotoxicity of heavy metals. According to empirical studies, due to the increased concentrations of bioavailable lead, copper, and arsenic, microbial diversity and enzymatic activities decrease in tailing-contaminated soils, especially (Sun et al., 2021). Simulated laboratory focusing ecotoxicological analysis using organisms like Daphnia magna, Eisenia fetida, and the roots plant elongation test are some of the studies increasingly combined with those in files to verify bioavailability information (Kong et al., 2024).

The aspect of phytotoxicities is another serious factor, since the exposure to metals such as nickel and chromium is able to cause oxidative stress as well as stunt the development of plants. As a result, an integrated assessment of the metal behavior including the associated risks can be provided in mining-affected soils by combining speciation analyses and ecotoxicological studies (Fernandez et al., 2020).

Human Health Risk Assessment

The high health risks presented by soils degraded due to mining activities by heavy metals is a relevant present day issue. These chemicals exhibit significant toxicity, long life and tendency to accumulate biologically thus necessitating the adoption of the complete human health risk assessment (HRA) models. HHRAs are aimed at measuring the probability of experiencing negative health effects after exposure to the hazard through ingestion, breathing and touching contaminated soils. Included in metals of particular interest are lead (Pb), cadmium (Cd) and arsenic (As) which have carcinogenic, neurotoxic, and nephrotoxic properties respectively (Yang et al., 2022; Zhang et al., 2023). Here is the rewritten version of your paragraph with proper structure and citation:

Soil pollution has serious toxicologicalconsequences for human health,particularly concerning exposure toheavy metals and persistent organicpollutants. For instance, exposure to leadand mercury can result in neurologicaldisorders, developmental delays, andcognitive impairments, especially inchildren. Arsenic exposure is associatedwith an increased risk of certain cancers,including skin and lung cancer. Chronicexposure to pesticides and dioxins hasbeen linked to hormonal disruptions,reproductive issues, and immune systemdamage, leading to long-term healthcomplications (Mohammed, et al., 2024).

A major contributor to soil contamination is unsystematic anthropogenic activity, particularly those associated with industrial operations. The rapid pace of urbanization, industrialization, and increasing population density has exerted significant pressure on the environment. These pressures are further intensified by evolving lifestyles and changing consumption patterns. Consequently, environmental issues such as soil pollution have become more pronounced, with their severity varying across regions and over time (Adam et al., 2024). Such dynamics underscore the need for region-specific assessments and interventions, especially in light of growing concerns about human exposure pathways and associated health risks (Adam et al., 2024).

New methodological developments include the implementation of advanced modeling tools like the USEPA Integrated Risk Information System (IRIS) and probabilistic risk models taking into account the variability in the exposure factors and receptor (Chen et al., 2021). The standard measures such as Hazard Quotient (HQ) and Lifetime Cancer Risk (LCR) are still essential in measuring the non-carcinogenic and the carcinogenic risks respectively. Recent research employs the significance of specific assessments depending on the territory level that includes heavy metal speciation information, instead of depending merely on the poorly-defined perception of total metal concentrations because total concentrations may also over- or underestimate the actual hazardous outcomes in the real world (Li et al., 2024).

Environmental Regulations and Guidelines

The control of the heavy-metal contaminated soils has been instituted by the concerned environmental protection agencies worldwide that have put in place strict measures on their control. Regulatory policies like EU Soil Strategy (2021), USEPA Regional Screening Levels (RSLs) and WHO health-based guidelines have benchmark limits that are allowable in various land-use scenarios. An example is the precautionary values in the European Commission (2022) which are 1 mg/kg in agricultural soils of cadmium and 50 to 300 mg/kg of lead depending on the soil. In China, contaminated land risk control responses stipulated in the Soil Environmental Quality Risk Control Standards (GB 36600-2018) determines various risk control limits in industrial, residential, and farms areas (Zhou et al., 2023). Such rules are now ensuring an increased inclusion of bioavailability and speciation data to consider ecological and human-health risks in a more accurate manner (Huang et al., 2023).

Remediation Strategies

The clean-up of mining-contaminated soils requires a combination of methods based on the nature of speciation and mobility of heavy metals. Traditional ones, that is, excavation and replacement, solidification/stabilization, and soil washing, are efficient, but in most cases expensive and environmentally invasive (Rahman et al., 2022).

More recent developments in use of phytoremediation, electro kinetic remediation, and the use of biochar, nanomaterials, and chelating agents provide alternatives that are more sustainable. The biochar obtained using agro-waste, in this case, has indicated a great efficiency in the immobilization of Pb and Cd when the pH of the soil and binding capacity of the soil is altered (Wang et al., 2023). In addition, microbial mediated remediation is also getting popularity due to its ability to modify metal speciation by changing redox generation and also by decreasing bioavailability of the metal (Liu et al., 2024).

Experimental approaches, including mixed corrections (e.g., biochar + clay minerals), nanomaterial-based sorbents, are considered to provide improved stabilization and reduce the threat of long-term effects to the environment (Ahmed et al., 2024). A detailed speciation analysis and risk assessment should dictate the choice of the remediation method to enable the selection of an effective approach that is ecologically safe and economically feasible.

In-Situ Remediation Techniques

In-situ remediation activities represent cost-efficient and environmentally friendly approaches to reduce heavy-metal pollution of mine-contaminated soils without excavating and/or transporting contaminated materials. The methods in question are phytoremediation, soil amendments, electrokinetics as well as remediation, and stabilization-solidification.

Phytoremediation (the use of hyperaccumulator species of plants) has made a come back in remediation research due to developments in the field of plant biotechnology and microbe-aided remediation. Evidence based on research shows that phytoremediation of genetically modified and native plants such as Brassica juncea and Pteris vittata can decrease the bio availability of arsenic and lead in contaminated soils (Yan et al., 2023; Zhang et al., 2022). The complementary studies also have shown that the metal uptake and tolerance are enhanced through interaction with soil microbes and arbuscular mycorrhizal fungi (Wang et al., 2024).

Electrokinetic remediation is a method of remediation that redirects the movement of metal ions by creating low-intensity electric fields into which the metal ions can be then removed or immobilised. Demonstration has been shown to be suitable in low-permeability clay soils, and its further optimisation involves coupled technologies with electro-bioremediation, and nanoparticle platforms that deliver (Rahman et al., 2021).

Common soil amendments, in particular, biochar, zeolites, and lime, are used to bind heavy metals, especially through adjusting soil pH, cation exchange capacity and redox potential. Most recently, biochar was found to do both, effectively immobilizing the heavy metals and at the same time stimulate the microbial activity, which will ensure the process of remediation continues over long periods of time (Chen et al., 2022; Liu et al., 2023).

Ex-Situ Remediation Techniques

Ex-situ remediation involves removal and off-site processing of soil already contaminated. It is more applicable than in-situ remediation because it is more disruptive and expensive but also offers decontamination controllability and faster process. Soil washing, chemical extraction, thermal desorption and stabilization at accredited treatment plants can be common.

Soil washing is based on the removal of heavy metals into aqueous solutions using surfactants, chelating agents or acid solutions; new generation biodegradable chelants, including ethylenediamine-diacetic acid (EDDS) and amino-polycarboxylates, have shown improved specificity and low environmental hazard (Zhou et al., 2022).

Thermal treatment is also effective in case of mercury and arsenic volatilization even though it is associated with enormous energy demand. Contemporary systems combine thermal desorption with vapor capture (and condensation) units so that secondary emissions formed can be counteracted (Singh & Patel, 2021).

These processes are termed stabilization where binders such as cement, fly ash and geopolymer matrices are applied to bind up the heavy metals in forms that are less soluble. The new development of geopolymer technology has led to environmentally sound and resistant matrices applicable in the stabilization of hazardous waste (Wang et al., 2023).

Future Research Directions

Despite significant advancements, several challenges persist in the remediation of heavy metal-contaminated soils. Future research should prioritize:

Development of nanomaterials and smart delivery systems for targeted remediation with minimal ecological disruption.

Real-time monitoring technologies, such as sensor networks and machine learning-based predictive tools for speciation and risk tracking.

Integrated remediation frameworks combining chemical, biological, and physical strategies to achieve holistic, site-specific solutions.

Climate-resilient remediation methods, considering how climate change affects metal mobility, speciation, and plant uptake. Furthermore, community participation and socio-economic factors should be integrated into remediation planning, especially in vulnerable, mining-impacted communities.

CONCLUSION

The speciation of the heavy metals in the mining affected soils is a critical factor in the determination of their mobility, bioavailability and resultant extent of ecological and health risks. Geometry, geochemical partitioning, and behavior of such contaminants need a thorough and complete understanding to narrow the risk assessments and remediation strategies. Though in-situ and ex-situ technologies have all shown significant potential, site-specific conditions as well as metal speciation and soil can often limit their efficacy. Remediation strategies in the future ought therefore to incorporate an interdisciplinary system which incorporates the innovation in environmental chemistry, biotechnology, materials science, and data analytics. With further research and suitable policy enhancement, there can be formulated sustainable and dynamic solutions to protect the ecosystem and human health against the aftermath of the heavy-metal contamination due to mining.

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