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Lead-Zinc Mining in Iran and its Soil Legacy: Potentially Toxic Elements and Implemented Remediation Strategies

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ABSTRACT

Lead-zinc mining supports national economies but generates soil contamination by potentially toxic elements (PTEs). This review synthesizes published evidence from Iranian lead-zinc regions, examines contamination trends, and discusses the remediation techniques employed. Across the reviewed Iranian studies, soils adjacent to mining operations commonly showed elevated Pb, Zn, and Cd, whereas As and Cu were reported less consistently and generally formed more localized hotspots that decreased with distance from source areas. Two principal transport mechanisms were prevalent: the wind-driven movement of fine tailings dust and the drainage from tailings and waste rock. These were influenced by the surrounding geology, with carbonate settings mitigating acidity but not reducing metal concentrations, while sulfide or shale environments promoted acid mine drainage and increased mobility. Four classes of remediation have been investigated. Among the remediation approaches reported in the reviewed literature, phytoremediation is predominantly utilized, with results frequently supporting phytostabilization using resilient native plants; however, genuine phytoextraction occurred rarely and is adapted to specific locations. Incorporating biochar (at approximately 1-3% w/w) reduced the mobility and bioavailability of of Pb, Zn, and Cd. Electrokinetic remediation was effective for fine-grained, saturated hotspots when electrolyte chemistry and pH fronts were controlled (e.g., citric-acid) and was best integrated into a treatment train. Biomineralization showed potential in calcareous settings, with laboratory evidence for carbonate co-precipitation/incorporation of Pb-Zn-Cd but still requires field validation and ammonium management. By matching treatments to site geochemistry and using standardized performance metrics, lead-zinc mine soils can be managed from hotspot control to durable, monitored risk reduction.

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INTRODUCTION

The mining industry is critically important in supplying essential mineral resources that support technological and socioeconomic development. However, intensive extraction and processing generate substantial quantities of waste materials, including crushed rock, overburden, and tailings, which are biologically inert, structurally poor, and often enriched in potentially toxic elements (PTEs) such as Cd, As, and Pb (Setu & Strezov, 2025). These elements occur in both primary minerals (e.g., sulfides) and secondary minerals (e.g., carbonates and sulfates of calcium and magnesium) (Haghighizadeh et al., 2024). Through ore milling, grinding, concentration, and disposal practices, as well as the generation of acid mine drainage (AMD) and wastewater, such wastes become primary sources of PTEs to surrounding environments (Rouhani et al., 2024). Among these materials, tailings represent the most critical hazard to soil and aquatic systems because of their fine particle size, elevated PTE concentrations, and high mobility. Once released, tailings and AMD effluents can disperse PTEs in particle-bound or dissolved forms, resulting in their accumulation in sediments, agricultural soils, water bodies, and food crops (Tyagi & Haritash, 2025).

The extent and risk of PTE contamination depend on the geochemical characteristics of tailings and receiving soils, which vary among sites (Hudson-Edwards et al., 2024). While assessments typically measure total metal concentrations, such values do not capture toxicity, bioavailability, or mobility. Because elements partition among distinct geochemical fractions with environment-dependent stability, only a portion of the total pool becomes mobilized under specific conditions (Ali et al., 2024; Rouhani & Hejcman, 2025). In general, PTEs are not fully bioavailable. Yet emissions from lead-zinc mining can, under acidifying, oxidizing, or saline conditions, become mobilized, dispersed, and deposited in various environmental components (Rouhani et al., 2025a). Such accumulation increases exposure risks that can directly or indirectly affect humans, animals, and plants. Accordingly, soil contamination by PTEs has received significant attention because of its persistence and harmful effects on biota (da Silva-Rêgo et al., 2022; Rouhani et al., 2023). In soils, PTEs can disturb microbial functioning by altering molecular structures, blocking functional groups, substituting essential metal ions, and, in severe cases, inhibiting soil respiration. These metals may also enter the food chain via plant uptake, as extensive root systems enable absorption of ionic compounds, including metals, even at low concentrations (Nieder & Benbi, 2024).

Mitigating these risks necessitates effective remediation of metal contaminated soils. Numerous physicochemical and biological strategies have been developed over the past decades (Afonso et al., 2020). Phytoremediation emerged as a low-cost, in situ option, and studies of metal-tolerant plants demonstrate inherent genetic features that promote uptake, stabilization, or sequestration of pollutants (Erickson & Pidlisnyuk, 2021). However, phytoremediation is less effective in severely polluted soils where plant growth is inhibited. To address these challenges, the use of biochar and other chemical or organic amendments has been shown to improve phytoremediation performance by supporting plant growth and stabilizing PTEs, especially in soils with high pollutant loads (Kumar et al., 2025). The efficacy of these methods, however, is strongly site specific and affected by parameters such as soil type and pH (Al Souki et al., 2025).

Despite extensive global work on lead-zinc mining, a comprehensive synthesis of mining-related soil contamination and remediation evidence for Iran remains lacking. Several studies have investigated soil contamination around lead-zinc mines in Iran and globally, but thorough reviews that integrate contamination levels with field outcomes of remediation remain limited. This gap is especially important because Iran contains numerous lead-zinc districts with diverse ore geology and climatic conditions, which shape exposure pathways and remediation performance. At the same time, the available Iranian literature is unevenly distributed among mining areas, with a substantial proportion of published evidence derived from a limited number of sites. Accordingly, the aim of this review is to synthesize the Iranian evidence base as currently available, while avoiding overgeneralization beyond the spatial coverage of published studies. In this context, this review (i) summarizes the major PTEs and their reported soil concentrations in Iranian lead-zinc mining areas, (ii) compares the Iranian evidence with selected international case studies, and (iii) evaluates remediation strategies that have been utilized and reported in the literature, emphasizing their efficacy and limitations under Iranian soil-climate conditions. By clearly associating contamination profiles with reported remediation outcomes and by explicitly identifying current geographic and methodological gaps in the literature, this review seeks to provide an evidence-based framework for risk reduction and future research in lead-zinc mining areas of Iran.

Lead-zinc mines in Iran

Iran contains several major lead-zinc deposits where soil and waste contamination by PTEs has been investigated. The Irankuh mine, located about 25 km southwest of Isfahan in the Sanandaj-Sirjan structural zone, is one of the country's most productive lead-zinc sites. The deposit contains an estimated 23 million tons of ore, averaging 7.4% Pb and 2.4% Zn, with an annual extraction of approximately 358,000 tons (Forghani et al., 2015). Ore is processed using flotation to produce concentrates, producing substantial quantities of tailings stored in ponds. The host rocks include Jurassic-aged shales, considered a potential source of lead-zinc mineralization (Ghazban et al. 1994).

The Ahangaran mine in western Iran is another long-operating site, with reserves estimated at 256,000 tons. Since the construction of flotation facilities in the 1970s, production has reached about 3,600 tons of Pb and Zn annually through open-cast mining (Mehrabi et al., 2015). The Nakhlak mine, located northeast of Anarak City in central Iran, is one of the oldest Pb mines in the country, with exploitation dating back nearly two millennia. Mineralization occurs in Upper Cretaceous limestone and fault zones, with galena (PbS) as the dominant ore. Mining is conducted underground using cut-and-fill techniques, and waste materials are typically disposed of in nearby regions without treatment (Moore et al., 2016). The Kushk mine, northeast of Bafgh in Yazd Province, has been in operation since the 1940s and was mechanized in the 1960s. It lies close to a processing plant, and wastes are commonly disposed of at the mine's margins, raising concerns about uncontrolled PTE dispersal (Sohrabizadeh et al., 2023).

The Angouran mine in Zanjan Province is the largest lead-zinc deposit in Iran and one of the most significant globally. Mining expanded after World War II, with large-scale open-pit extraction initiated in the 1960s. The deposit is composed mainly of carbonate ores (about 80% of reserves), with the remainder in sulfide form (Borg, 2005, Zarei et al., 2008). Waste products are often released into the environment without treatment, making Angouran a major source of regional soil and water contamination (Parizanganeh et al., 2010).

Collectively, these mines demonstrate the twofold importance of lead-zinc resources in Iran: they are crucial to national metal production yet also hotspots of PTE release due to improper waste management. Although their geological settings and ore processing practices create site-specific contamination pathways, a systematic problem emerges across the sector: the consistent accumulation of untreated tailings and waste rock in the local environment. This pattern suggests that the inadequacies in waste management are not restricted to single mines but represent a more widespread structural problem within Iran's lead-zinc sector (Figure 1).

Potentially toxic elements in Pb-Zn mine areas

Mining and processing of lead-zinc ores generate significant quantities of waste rock and tailings. These materials are commonly disposed of with limited or no environmental controls (Arenas-Lago et al., 2018). Proper management and disposal of tailings are a major environmental

Fig. 1. Locations of lead-zinc mines in Iran

concern that has intensified with increased exploration and the exploitation of lower-grade deposits (Ozkan and Ipedoglu, 2002). The negative effects of tailings ponds arise from high PTE concentrations, limited vegetation, low organic matter, and often acidic conditions (Favas et al., 2011). PTEs are exported to adjacent soils via AMD and windborne dust, processes that accelerate weathering and contaminant release (Ferreira da Silva et al., 2004). Newly formed mine soils are classified as spolic Technosols (IUSS Working Group WRB, 2015). Their poor structure, extreme pH, and low organic matter inhibit the establishment and functioning of plants, animals, and microorganisms (Arenas-Lago et al., 2018).

Table 1 summarizes published studies on lead-zinc mining soils in Iran, and Table 2 reports concentrations of the primary pollutants. Corresponding to elemental correlations, Figure 2a,b shows that Pb (n = 27), Zn (n = 26), and Cd (n = 21) are the most frequently analyzed, and they also dominate among the most frequently reported pollutants, Pb (n = 27), Zn (n = 21), Cd (n = 17), whereas As (n = 6) and Cu (n = 5) are identified less often and Mn/Sb only occasionally (n = 1). From Table 2, indicative ranges across Iranian sites are: Pb ≈ 41–16700 mg·kg^{-1}, Zn ≈ 52–12963 mg·kg^{-1}, Cd = 0.26–81.10 mg·kg^{-1}, and Cu = 0.39–8804 mg·kg^{-1}.

Iranian case studies: Soils near the Ahangaran mine (Malayer, western Iran) showed significant Pb, Sb, and Cd from mining activities (Rafiei et al., 2010). In the same district, Pb and Zn decreased with distance from the mine, indicating localized dispersion (Mehrabi et al., 2015). In the Nakhlak mine area (central Iran), alkaline soils with low organic matter contained elevated Pb and Zn associated with mineralized veins and mining (Moore et al., 2016). Agricultural soils adjacent to the Nakhlak mine showed moderate to heavy Pb and Zn and variable Cd and Cu, while Mn and Ni were largely unaffected (Baghaie and Aghili, 2019b). Around the Irankouh lead-zinc mining district, agricultural soils were heavily contaminated with Zn, Pb, and As. Dispersion was driven primarily by dust rather than water pathways, with Zn showing greater spatial dispersion than Pb and As (Geranian et al., 2013). In the same district, Forghani et al. (2015) reported comparable Ni, Cu, and Cr in agricultural and mine

Table 1. Conducted soil pollution studies in lead-zinc mine areas in Iran

Study area	Analyzed PTEs	Most polluted PTEs	Analyzed method	References
Irankouh	Ag, As, Al, Ba, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V, Zn	As, Cd, Pb, Zn	ICP-OES	Tehrani et al. (2025)
Kushk Mine	Pb, Zn, Cr, Co, Sb, Ba	Pb, Cd, Ba	ICP-OES	Ghaneei-Bafghi et al. (2024)
Zardgol Mine	As, Cd, Cu, Ni, V, Cr, Pb, Ba, Mn, Zn	Pb, Zn, Cd	AAS	Karami et al. (2023)
Angouran	Co, Cr, Cd, Pb, Zn	Pb, Cd	Not given	Hosseinniaee et al. (2023a)
Kushk Mine	Pb, Zn, Fe, Mn, Cd, Cu	Pb, Zn, Cd, Cu	AAS	Sohrabizadeh et al. (2023)
Bama Mine	Fe, Pb, Zn, Cu, Ni, Cd, As	Pb, Zn, Cd	AAS	Hemmat-Jou et al. (2021)
Marjanabad mine	Zn, Ni, Sb, Pb, Mo, Cu, Cr, Co, Cd, As	Pb, Zn, As	ICP-MS	Kazemi, (2021)
Irankouh	Pb, Cd, Zn, Cu	Pb, Zn, Cd	AAS	Abouian Jahromi et al. (2020)
Shahin mine	Pb, Cd	Pb, Cd	AAS	Baghaie & Aghili, (2019a)
Nakhlak mine	Mn, Cu, Ni, Zn, Cd, Pb	Pb, Zn	ICP-MS	Baghaie & Aghili, (2019b)
Tang-e Douzan mine	Mg, Cd, Zn, Pb	Pb, Zn, Cd	AAS	Hesami et al. (2018)
Nakhlak mining district	Zn, Sb, Pb, Ni, Mo, Cu, Cr, Co, Cd, As, Ag	Pb, Zn	ICP-MS	Moore et al. (2016)
National Iranian Lead and Zinc	As, Co, Cr, Fe, Mn, Cd, Ni, Pb, Zn	As, Cd, Pb	ICP-AES	Karbassi et al. (2016)
Irankouh	Cd, Cu, Ni, Zn, Pb	Pb, Cd	AAS	Nekoeinia et al. (2016)
Irankouh	Fe, As, Cd, Zn, Pb	Pb, Zn, As	ICP-OES	Mokhtari et al. (2015)
Kushk Mine	Pb, Zn, Ag	Pb, Zn	AAS	Mahdavian et al. (2015)
Irankuh	Ni, Zn, Pb, Cu, Cr, Cd, As	Pb, Zn, Cd, As	ICP-OES	Forghani et al. (2015)
Ahangaran mining district	Zn, Sb, Pb, Cu, Cd, As, Ag	Pb, Zn, Cu	ICP-MS	Mehrabi et al. (2015)
Lakan mine	Ni, Cu, Co, Zn, Cd, Pb, Hg	Pb, Zn, Cd	AAS	Ghomi et al. (2013)
Ahangaran	Cd, Cu, Zn, Pb	Pb, Zn, Cd, Cu	ICP-OES	Cheraghi et al. (2013)
Irankouh	Pb, Zn, As	Pb, Zn, As	ICP-OES	Geranian et al. (2013)
Irankouh	Zn, Pb	Pb, Zn	AAS	Ghaderian et al. (2012)
Ahangaran	Fe, Pb, Cu, Mn, Zn	Pb, Zn, Mn	ICP-OES	Lorestani et al. (2012)
Angouran	Ni, Pb, Zn, Mn, Cu, Co	Pb, Zn, Cu	AAS	Boojar & Tavakkoli, (2011)
Ahangaran	Sb, As, Cd, Cu, Zn, Pb	Pb, Sb, Cd	ICP-AES	Rafiei et al. (2010)
Angouran	Pb, Zn, Cd	Pb, Zn, Cd	AAS	Parizanganeh et al. (2009)
Waste pool soil of Angouran mine	Cd, Cu, Fe, Ni, Pb, Zn	Pb, Zn, Cd, Cu	AAS	Chehregani et al. (2009)

soils, but higher Zn, Pb, As, and Cd in mine soils, pointing to tailings ponds. Subsequent work in Irankouh found agricultural soils with moderate to strong Pb and heavy to extremely high Cd; Cd inputs were partly attributed to fertilizers, wastewater, and sewage sludge, while Pb, Zn, and Cu indicated both mining and agrochemical sources (Nekoeinia et al., 2016). More recent sampling within the district detected high Pb, Cd, and Zn in residential areas near the mine, indicating ongoing impacts on nearby communities (Abouian Jahromi et al., 2020). This concern was further confirmed by Tehrani et al. (2025), who showed that PTE contamination in soils and edible crops around the Irankouh Pb-Zn mine was associated with significant human health risks, particularly via ingestion and particularly for children. Their findings also identified As and Cd as the main contributors to carcinogenic risk and showed that risk estimates based on

Table 2. Concentration of most pollutant PTEs (mg·kg⁻¹) in lead-zinc mine soil

Study areas	PTEs					References
	Pb	Zn	Cd	Cu	As	
Irankouh	296	1659	2.5	31.9	18	Tehrani et al. (2025)
Kushk Mine	1613	463	na	na	na	Ghaneei-Bafghi et al. (2024)
Zardgol Mine	197.22	492.28	56.2	63.90	28.19	Karami et al. (2023)
Kushk Mine	40.92	51.92	0.26	0.39	na	Sohrabizadeh et al. (2023)
Bama Mine	723	668	22.31	172	90.27	Hemmat-Jou et al. (2021)
Marjanabad mine	6073	7826	12.15	58	234	Kazemi, (2021)
Irankouh	281	1035	2.53	38.4	na	Abouian Jahromi et al. (2020)
Shahin mine	234	na	1.89	na	na	Baghaie & Aghili, (2019a)
Nakhlak mine	354	347	2.72	36.47	na	Baghaie & Aghili, (2019b)
Tang-e Douzan mine	1480	976	29	na	na	Hesami et al. (2018)
National Iranian Lead and Zinc	51.35	126.81	4.63		17.23	Karbassi et al. (2016)
Nakhlak mining district	4950	2076	15.4	42.3	26	Moore et al. (2016)
Irankouh	51.80	60.34	1.38	12.05	na	Nekoeinia et al. (2016)
Irankouh	711	4031	5.5	34.1	30.8	Forghani et al. (2015)
Ahangaran mining district	1284	156	0.51	55.90	31.44	Mehrabi et al. (2015)
Irankouh	180	450	na	na	22	Geranian et al. (2013)
Lakan mine	3202	10564	36	210	na	Ghomi et al. (2013)
Ahangaran	1810	628	13	216	na	Cheraghi et al. (2013)
Ahangaran	8955	12963	na	120	na	Lorestani et al. (2012)
Angouran	1416	2217	na	426	na	Boojar & Tavakkoli, (2011)
Ahangaran	1901	476	2.7	8804	na	Rafiei et al. (2010)
Angouran	128.51	606	3.46	na	na	Parizanganeh et al. (2009)
Waste pool soil of Angouran mine	16700	2950	81.10	162	na	Chehregani et al. (2009)

Note: na: not analyzed

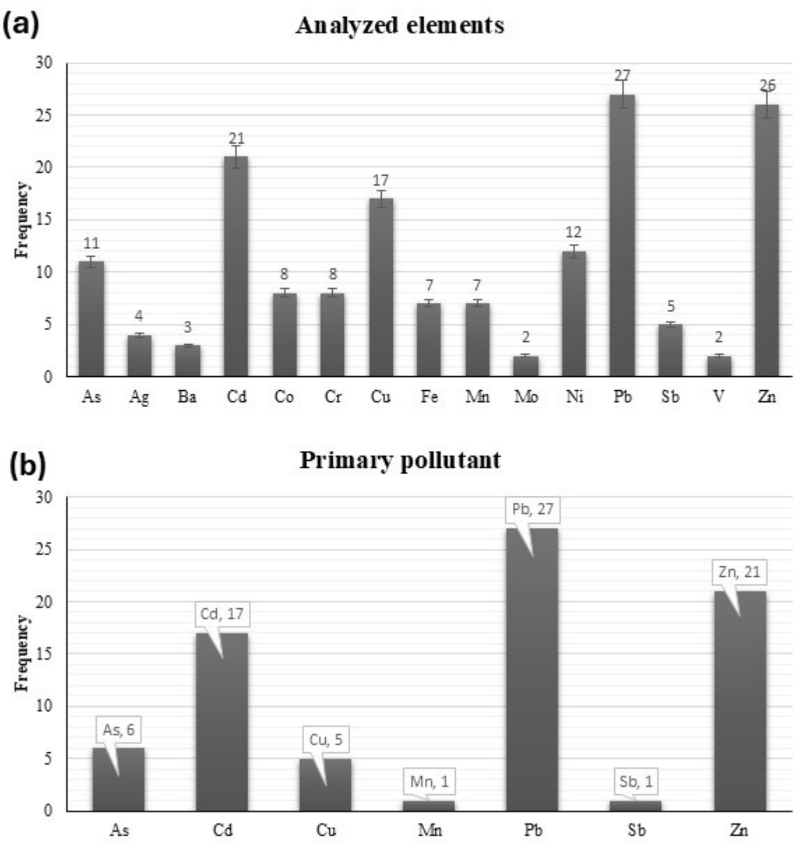

Fig. 2. (a) all analyzed elements and (b) primary pollutants in lead-zinc mine soil from Iran

bioaccessible concentrations were lower than those based on total concentrations, highlighting the importance of bioaccessibility-based assessment in mining-affected areas.

Soils from the Lakan lead-zinc mine exhibited elevated Pb, Cd, and Zn (Ghomi et al., 2013). Around the Shahin mine (Shazand County), mean Cd and Pb exceeded background values, implying potential health risks (Baghaie & Aghili, 2019a). In Zanjan Province, soils near the National Iranian Lead-zinc Company showed high Zn, Pb, As, and Cd, with Cd identified as the most bioavailable contaminant (Karbassi et al., 2016). At the Kushk Mine, elevated Zn, Pb, and Cd were associated with acidic, toxic wastes (Sohrabizadeh et al., 2023). Consistent with this, subsequent evidence from the Koushk Pb-Zn mining area showed that agricultural soils at the mine margins were more contaminated than nearby rangeland soils, with Pb and Zn concentrations exceeding environmental standards by several fold. Spatial differences between nearby villages at similar distances from the mine further suggested that, in addition to mining influence, local parent material geochemistry and agricultural management practices contributed to contamination variability (Ghaneei-Bafghi et al., 2024). In the Zardgol Pb-Zn mining area, soils did not show uniform PTE contamination overall, although localized enrichment of Pb, Zn, and Cd was observed, suggesting that contamination hotspots were mainly controlled by mineralized parent materials (Karami et al., 2023).

The wide PTEs concentration ranges reported in Table 2 likely reflect both environmental heterogeneity and, to a lesser extent, methodological differences among studies. The collected data cover different sample types, including mine wastes, highly contaminated soils close to mining sources, and more distant agricultural or residential soils, which are expected to differ substantially in contamination level. The reported variability is also influenced by differences in source intensity, proximity to tailings and processing areas, ore mineralization, host lithology, weathering, and secondary dispersion. In addition, inter-study comparability may be affected by differences in digestion procedures and, less importantly, analytical techniques; however, such methodological variation is unlikely to explain the full magnitude of the observed PTE ranges.

Global context: Similar patterns are reported worldwide: extended Pb and Zn contamination from tailings in East Greenland (Johansen et al., 2008); multi-element enrichment in India's Zawar district (Anju & Banerjee, 2012); reduction with distance of Zn, Pb, Cd, and As around former mines in Spain and Nigeria (Rodríguez-Seijo et al., 2020; Ozobialu et al., 2020); and multiple Chinese districts where tailings discharge Pb and Cd to paddy soils (Sun et al., 2022), smelting/mining/transport drive Zn-Pb-Cd accumulation (Zhang et al., 2023), and Inner Mongolia shows Cd and As with high ecological risk (Wang et al., 2023). These instances resemble the Iranian profile, dominated by Pb, Zn, and Cd; dispersion declines with increasing distance; tailings and smelting are major sources, highlighting a common management challenge in which inadequate waste storage can intensify near-field hotspots, including in Iran.

Implications and gaps: Current evidence is dominated by single-time, total-concentration surveys, with limited reporting of bioavailable fractions, mineral phases, dust deposition, groundwater and near-surface flow, or uncertainty. Sampling designs are uneven across districts and rarely standardized, limiting source apportionment and trend detection. Cross-study comparison is also limited by incomplete reporting of individual PTEs, since several studies did not quantify or report the same set of elements. A practical priority is the implementation of coordinated, cross-media monitoring networks in accordance with dominant wind and drainage corridors that jointly measure soils, dust fallout, and surface/near-surface waters and include routine speciation analyses. To reduce risk in the short term, efforts should focus on stabilizing tailings and waste-rock surfaces through surface covers, revegetation, dust suppression, and drainage management, while long-term actions should involve amendment-assisted phytoremediation. There are still deficiencies in management: adopting uniform protocols for sampling and reporting, mandating post-closure monitoring needs, and creating a national database for georeferenced mining-soil data would enhance comparability, transparency, and accountability.

APPLIED REMEDIATION STRATEGIES

The subsequent subsections analyze the remediation strategies reported for Iranian lead-zinc mining regions, including phytoremediation, biochar amendment, electrokinetic remediation, and biomineralization, while recognizing that the available evidence is concentrated in a limited number of sites, and evaluate their effectiveness in relation to local soil and climatic conditions.

Phytoremediation

Phytoremediation is widely regarded as a low-cost, in situ, and environmentally friendly approach for managing metal-polluted soils (Lavanya et al., 2024; Rouhani et al., 2025b). Because vegetation can be established without major soil disturbance, plant-based methods have been extensively tested in lead-zinc mining areas to limit dust and drainage pathways and, where feasible, extract PTEs from the rooting zone. Field performance is highly site specific and depends on metal bioavailability, soil chemistry, climate, and the depth and heterogeneity of contamination. This section synthesizes field evidence from Iranian lead-zinc districts, highlighting species that have demonstrated effectiveness under local conditions and the site factors that govern outcomes.

In the Angouran lead-zinc mining area, increasing PTE loads reduced arbuscular mycorrhizal fungi (AMF) sequence-type richness, colonization metrics, and spore numbers in roots of *Veronica rechingeri*; some AMF sequence types were restricted to the most and least contaminated sites (Zarei et al., 2008). A subsequent Angouran survey identified accumulator candidates: among five species (*Scariola orientalis, Noea mucronata, Gundelia tournefortii, Polygonum aviculare, Amaranthus retroflexus*), *N. mucronata* showed the highest shoot accumulation of Ni, Cd, Cu, Zn, and Pb, while *A. retroflexus* accumulated Fe; the experiment indicated soil PTE decreases in the presence of *N. mucronata* (Chehregani et al., 2009). Invasive plants on Angouran tailings adopted differing strategies: *Peganum harmala* primarily excluded PTEs, whereas *Zygophyllum fabago* accumulated them (Boojar & Tavakkoli, 2011). Fungal screening from Angouran soils found *Trichoderma harzianum* most tolerant to Cu, Zn, Pb, and Cd; *Acremonium persicinum* showed the highest Zn biosorption and *Penicillium simplicissimum* the highest Cu biosorption, supporting microbial-assisted approaches (Mohammadian et al., 2017). More recently, ethylenediaminetetraacetic acid (EDTA) assisted phytoextraction tests using Angouran mine soil showed increased Pb, Cd, and Zn uptake by *Marrubium cuneatum, Stipa arabica*, and *Verbascum speciosum*, although higher EDTA doses reduced chlorophyll content and biomass, indicating a compromise between metal uptake and plant performance (Hosseinniaee et al., 2023b).

At Tang-e Douzan, no hyperaccumulators were identified among 69 surveyed species; however, several natives were suitable for phytostabilization, *Ranunculus hybridus subsp. dodecandra, Ornithogalum orthophyllum, Medicago neglectum*, and *Cardaria falcata* (Cd/Zn), and *M. neglectum* and *Carex dichotomum* (Pb) (Hesami et al., 2018). Consistent with the importance of local plant adaptation in this mining area, Salehi-Eskandari et al. (2024) showed that *Marrubium cuneatum* collected from the Tang-e Douzan Pb-Zn mine exhibited greater tolerance to Pb than a non-metalliferous population, particularly under high Pb exposure. The metalliferous population also maintained higher biomass and accumulated relatively high Pb concentrations in shoots, indicating local adaptation to Pb contaminated conditions and suggesting potential suitability for Pb phytoextraction. In the Kushk mining area, *Mentha longifolia, Erodium cicutarium, Achillea wilhelmsii,* and *Nonea persica* were recommended for Zn and Pb stabilization, with *Peganum harmala* effective for Pb (Mahdavian et al., 2015). In Marjanabad lead-zinc mining areas, *Stachys byzantina* showed Pb-hyperaccumulation potential (Kazemi, 2021). In the Bama district, *Scrophularia inflata* tolerated high Pb and Zn; inoculation with metal-tolerant rhizobacteria and earthworms increased metal availability to mycorrhizae and enhanced plant uptake (Mahohi & Raiesi, 2019). A related assisted-remediation study from the same district showed that chelate application increased Pb and Zn availability in contaminated soil cultivated with sunflower and canola, with the response depending on chelate type, application rate, and plant species; among the tested amendments, hydroxylethylenediaminetetraacetic acid (HEDTA) was the most effective (Baghaie & Polous, 2019). In the Ravanj lead-zinc mining area, native metallophytes differed in PTE accumulation and distribution: Cd, Zn, Pb, and Mn were more strongly accumulated in shoots of some species, whereas Co, Cr, Cu, and Ni were retained more in roots of others. Among the investigated taxa, *Acantholimon hohenackeri* showed the highest transfer factor, mainly for Pb, while *Euphorbia macroclada* exhibited the highest Cd bioconcentration (Samimi & Shahriari-Moghadam, 2024).

Around the Ahangaran lead-zinc mine, *Scrophularia scoparia* was recognized as the most efficient plant for Pb stabilization; *Cirsium congestum* and *Centaurea virgata* for Mn, and *Scariola orientalis, Echinophora platyloba,* and *C. virgata* for Zn (Nouri et al., 2011). Additional research in Ahangaran reported hyperaccumulation behavior for *C. virgata* and *Euphorbia macroclada* for specific PTEs (Lorestani et al., 2012). More recently, rangeland plants contributed to Pb and Zn remediation near Ahangaran: *Scariola orientalis subsp. orientalis* showed the highest root uptake (Pb, Zn), while *Astragalus glaucacanthus* showed the highest aerial uptake; *Ebenus stellata, Acantholimon olivieri*, and *A. glaucacanthus* exhibited the highest Zn translocation factors, with similar trends for Pb (Kord et al., 2018).

These case studies indicate that phytostabilization with tolerant native or locally adapted species is the most consistently supported outcome on tailings and mine affected soils, whereas evidence for phytoextraction is more limited and remains strongly dependent on species and site (e.g., *Noea mucronata* at Angouran, Pb related hyperaccumulation potential in *Stachys byzantina*, and hyperaccumulator behavior reported for *Centaurea virgata* and *Euphorbia macroclada* at Ahangaran). Effectiveness is determined primarily by metal bioavailability, soil chemistry, and plant adaptation to contaminated conditions. High PTE loads can suppress AMF richness, colonization, and spore production, whereas biological interactions, including AMF associated systems, metal tolerant rhizobacteria, fungal inoculants, and, in some cases, earthworms, may modify remediation performance by influencing metal availability and plant uptake. Amendment assisted approaches have also shown potential, but their effects are dependent on the context. In particular, EDTA- and HEDTA-assisted systems increased Pb, Cd, and Zn uptake in Angouran and Bama soils, although stronger chelate treatment also reduced chlorophyll content and biomass in some cases, indicating a trade-off between enhanced metal uptake and plant performance. Therefore, the reviewed evidence supports phytostabilization as the more robust field outcome, while extraction oriented approaches appear suitable only in selected cases where adequate shoot accumulation and translocation have been demonstrated.

Biochar

In soils affected by mining and mine tailings, biochar can stabilize PTEs, improve water-holding capacity and structure, and promotes the growth of beneficial microorganisms, thereby creating conditions favorable for better plant cover (Chandra et al., 2023). Its efficacy is attributed to a high surface area, mineral ash content, and the occurrence of oxygen-rich functional groups. These characteristics are highly relevant in altering metal speciation and impacting plant absorption in contaminated lands (Gusiatin & Rouhani, 2023).

Near the Ahangaran lead-zinc district, sewage-sludge biochar increased residual and decreased exchangeable Pb and Cd, altering speciation and lowering mobility; performance varied with pyrolysis temperature (600 °C vs. 300 °C) through changes in pore/surface properties and corresponded with stronger declines in exchangeable metals (Karimi et al., 2020). At Bama lead-zinc mine site, walnut-leaf biochar reduced Pb and Zn in plant tissues and shifted metals from exchangeable/soluble and Fe–Mn oxide/carbonate pools toward organic/residual fractions, improving maize growth (Kabiri et al., 2019). Further investigation showed that 2% (w/w) biochar produced at 600 °C stabilized Pb(II) and Zn(II) and slowed release kinetics in contaminated calcareous soil (Kabiri et al., 2021). Extending these findings, Kabiri et al. (2024) reported that treatment of Pb contaminated calcareous soil from the Bama Pb-Zn mine with 2% biochar decreased both DTPA extractable Pb and Pb release rates relative to the control, while kinetic analysis showed that simplified Elovich, power function, and first-order models best described cumulative Pb release. Across these studies, biochar consistently shifts Pb, Zn, and Cd from labile to less available fractions, reduces plant uptake, and mitigates phytotoxicity, with strong performance in calcareous, organic-poor mine soils. Effective implementations incorporate biochar into cover layers or the upper 10–20 cm, pair it with phytostabilizing vegetation (and, where appropriate, microbial inocula), and assess success using fractionation and plant-uptake metrics rather than totals alone (Manikandan et al., 2023). Key gaps remain, short monitoring durations and insufficient reporting on aging/leaching and co-contaminants, so longer field trials with standardized speciation metrics would strengthen the case for widespread adoption.

Electrokinetic remediation

Electrokinetic remediation utilizes a low-voltage electric current field across contaminated matrices to mobilize dissolved species. It is most applicable to fine-grained, low-permeability tailings/soils where hydraulic leaching is inefficient (Karaca et al., 2016; Rezaee et al., 2019). At the Lakan lead-zinc flotation plant (Iran), electrolyte management strongly influenced outcomes: 1 M citric acid in the catholyte resulted in the highest Zn removal (38.34%), and using 1 M citric acid in both chambers led to the highest Pb removal (51.31%); higher acetic-acid concentrations also improved removals (Asadollahfardi et al., 2021). These patterns, strong sensitivity to conditioning chemistry and pH-front control, are consistent with results from other mining districts: in Türkiye, EDTA (0.05 M) did not significantly improve performance in highly polluted tailings (Demir et al., 2015); in Çanakkale, using 1 V cm^{-1} for 9 days removed ~20% Pb and Fe, with higher removals when the acid front advanced and run time increased (Karaca et al., 2016). Pre-acidification with concentrated H_2SO_4 has also increased net removals to ~31.9% Mn and ~18.0% Zn from real tailings (Ortiz-Soto et al., 2019).

The majority of electrokinetic remediation research focuses on silty-clayey, low-permeability tailings, whereas the results in sandy or heterogeneous deposits are usually less consistent and generally lower (Ammami et al., 2015; Hahladakis et al., 2016; Demir et al., 2015). The choice of chelating agents and the conditioning of electrolytes are critical: biodegradable organic acids such as citric acid may be more effective than low-dose EDTA with high concentrations of metals, though pre-acidification with strong acids enhances desorption, it also increases operational and waste management challenges. Effective designs manage pH fronts (acidified catholyte, carbonate control), maintain moisture continuity, and apply adequate voltage and run time with optimized electrode spacing. Electrokinetic remediation is ideally implemented for well-defined hotspots or as part of a treatment train (Electrokinetic + metal recovery + electrolyte treatment), instead of as a single treatment for entire tailings deposits (Asadollahfardi et al., 2021).

Biomineralization

Biomineralization involves the biologically facilitated creation of minerals that can immobilize dissolved metals through mechanisms such as co-precipitation, adsorption, or lattice substitution (Barkay and Schaefer, 2001). In the context of Iranian lead-zinc mining areas, however, the available evidence reviewed here mainly concerns microbially induced calcite precipitation (MICP), and the following discussion is therefore focused on this pathway. MICP, typically driven by ureolysis, raises pH and carbonate alkalinity and promotes CaCO3 precipitation (Alonso et al., 2017). MICP has been studied for ground improvement, CO_2 sequestration, and contaminant control, but field utilization for PTE remediation remains developing (Anbu et al., 2016). During MICP, PTEs can be immobilized by partial substitution for Ca^{2+} within carbonate lattices and by co-precipitation or surface sorption onto newly formed carbonate minerals (Achal et al., 2011). Laboratory systems frequently report high apparent solution removals over short incubations (Li et al., 2013), but these reflect controlled conditions. In calcareous soils from the Angouran mine, urease-producing bacteria supported carbonate biomineralization of Cd, Pb, and Zn: *Stenotrophomonas rhizophila* removed 96.25% Pb, 71.30% Cd, and 63.91% Zn after 72 h incubation; *Variovorax boronicumulans* removed 95.93% Pb, 73.45% Cd, and 73.81% Zn; and *Sporosarcina pasteurii* achieved 98.71% Pb, 97.15% Cd, and 94.83% Zn under similar conditions (Jalilvand et al., 2020).

MICP is promising for immobilizing Pb–Zn–Cd in carbonate-buffered, calcareous mine soils, where alkalinity and Ca^{2+} availability favor metal co-precipitation/incorporation. Key controls include urease activity, pH and dissolved inorganic carbon, Ca^{2+} supply compared to competing cations, and pore-scale transport. The substantial removal rates observed in short-term batch experiments should be considered as preliminary evidence of concept effectiveness; verification in the field warrants focusing on ammonium management, the long-term stability of metal carbonates under varying pH/redox conditions, and the risk of pore clogging.

CONCLUSION AND FUTURE PERSPECTIVES

Lead-zinc mining in Iran has created localized soil hotspots of Pb, Zn, and Cd, with As and Cu reported less consistently. These hotspots were driven mainly by tailings dust and drainage from tailings/waste rock. Their intensity and mobility were further influenced by host geology; carbonate settings buffer acidity but not metal loads, whereas sulfide/shale settings favor higher mobility. Across the reviewed literature, phytostabilization with tolerant native species appeared as the most reliable, field-scale outcome; phytoextraction was uncommon and site-specific and required secure biomass handling. When amended with biochar, particularly at concentrations of around 1–3% w/w, there was a consistent shift of Pb/Zn/Cd from more mobile to less accessible forms, reducing plant absorption and enhancing vegetation coverage in mine-contaminated soils, which were frequently calcareous. Electrokinetic remediation was effective for fine-grained, saturated hotspots when electrolyte chemistry and pH fronts were controlled (e.g., citric-acid conditioning) and was best used within a treatment process rather than across entire deposits. MICP showed potential in calcareous settings for carbonate co-precipitation/incorporation of Pb-Zn-Cd, but requires field validation and by-product management. Although this review synthesizes current knowledge on the distribution, mobility, and management of PTEs in Iranian lead-zinc mining areas, an important limitation of the available literature is its concentration in a limited number of sites, which limits broader spatial generalization across Iranian mining regions. This limitation also highlights a priority for future work, in particular the need to expand field investigation and remediation assessment to underrepresented lead-zinc districts in order to build a more geographically representative basis for national-scale evaluation. At the same time, important gaps remain in linking remediation performance with human exposure reduction and long-term risk management. Accordingly, the following research and implementation priorities are recommended:

Monitoring and risk assessments are recommended to specifically consider wind, precipitation, and temperature. Seasonally resolved sampling and season-by-season reporting would help distinguish dry-season aeolian transport from wet-season drainage, capturing dust pulses and hydrologic mobilization. To clarify dust pathways and off-site exposure, downwind fluxes of tailings-derived particles from dumps and processing areas should be evaluated by combining deposition collectors and distance-gradient transects with soil surveys in agricultural and residential zones, linking sources to off-site burdens and potential food-chain entry. Monitoring scope is recommended to extend beyond tailings piles to surrounding soils along wind and drainage corridors, with georeferenced transects used to track concentration reduction with distance and to identify hotspots at land-use interfaces. Multi-season and long-term monitoring is recommended to record aging and leaching, and metrics should be standardized across studies, such as BCF/TF for plants and release-rate kinetics for amended soils, to enhance comparability and support broader cross-site comparison. Therefore, these steps would help develop a stronger and more geographically representative evidence base for remediation planning in Iranian lead-zinc mining areas.

AUTHOR CONTRIBUTIONS

Abdulmannan Rouhani: Conceptualization, Literature search, Data curation, Investigation, Writing original draft, Writing, review & editing. **Amir Hossein Dashtian:** Writing, review & editing. **Nader Sayedi:** Writing, review & editing. **Mohammad Reza Elmi:** Review & editing. **Ghazwa Basma**: Review & editing. **Karim Suhail Al Souki:** Critical revision. All authors reviewed the results and approved the final version of the manuscript.

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