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Phytoremediation strategies for remediating potentially toxic elements' polluted soils in lead-zinc mining areas: A critical review

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Abstract

Lead–zinc mining activities generate highly degraded soils enriched with potentially toxic elements (PTEs), characterized by acid-generating tailings and low fertility, which collectively inhibit vegetation establishment and ecological recovery. This review synthesizes findings from studies on phytoremediation and assisted phytoremediation in lead-zinc mining regions worldwide. Phytostabilization was the dominant process, with Pb largely immobilized in the roots and showing minimal movement through the plant. In contrast, Zn showed higher mobility, allowing for occasional phytoextraction. Pioneer shrubs and xerophytic grasses effectively stabilized nutrient-poor, metal-rich soils in Mediterranean and North African sites, while deep-rooted woody plants restricted contaminant migration through root immobilization. Genuine hyperaccumulators were rare, suggesting that local metal tolerance rather than hyperaccumulation is the dominant adaptive mechanism. Assisted systems enhanced remediation efficiency: arbuscular mycorrhizal fungi (AMF) and earthworms improved fertility and reduced Pb and Zn mobility, whereas plant growth–promoting rhizobacteria (PGPR) and endophytes stimulated growth but had variable effects on metal mobility. Biochar consistently decreased Pb, Zn, and Cd bioavailability, improved soil pH and nutrient status, and supported vegetation, though its effectiveness depended on feedstock and dose. In conclusion, phytostabilization using tolerant native vegetation, supplemented by microbial or biochar amendments, represents the most reliable and sustainable remediation pathway in lead-zinc mining areas, whereas phytoextraction remains restricted to specific Zn tolerant species.

Keywords: Lead-zinc mine; earthworms, plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, biochar

1. Introduction

Soil contamination caused by mining activities, particularly lead-zinc mining, constitutes a major environmental hazard influencing regions involved in such endeavors (Pérez *et al* 2024). The impact of lead-zinc mining operations leads to significant soil destruction across extensive areas, located behind degraded land, that can extend the detrimental environmental effects even after the cessation of mining activities (Rouhani *et al* 2025; Asare *et al* 2024). Tailings and waste rock dumps often release pollutants to surrounding areas, and their environmental impact frequently surpasses the direct effects of mining activities themselves (Buch *et al* 2024; Yıldız *et al* 2024). The deposition of tailings results in the formation of spolic technosols, which are young soils that develop on unstable materials characterized by low cohesion (Rouhani *et al* 2024). Such soils exhibit physical, chemical, and biological deficiencies caused by low nutrient and organic matter content, elevated levels of potentially toxic elements (PTEs) that essentially restrict the development of plants, animals, and microorganisms (Ba *et al* 2024; Haghighizadeh *et al* 2024; Hudson-Edwards *et al* 2024). Among the elements commonly found in Pb–Zn mining soils, Pb, Zn, Cd, and Cu are the most abundant, as reported by a comprehensive review by Rouhani *et al* (2025).

The primary drivers of PTEs in lead-zinc mining areas include mining operations, i.e.: production, processing, waste management, and atmospheric deposition (Dehkordi *et al* 2024). Soil contamination around these mining sites often occurs as a result of the dumping and accumulation of mineral tailings containing PTEs. Due to the discharge of suspended assortments that carry PTEs into the air, these particles may settle in the vicinity of the contaminated site territories and contribute to additional contamination (Luo *et al* 2023). The discharge and mobility of PTEs are influenced by extraction and processing methods, which depend on ore deposit genesis. Tailings rich in sulfides can generate acid mine drainage, mobilizing PTEs and intensifying contamination in nearby soils and waters (Biamont-Rojas *et al* 2023). In general, open pit methods of extraction emit higher levels of pollution than underground approaches (Munanku *et al* 2023). The mineralization type and metal content in the ore can influence the release of PTEs (Yamazaki *et al* 2021). Moreover, older mines frequently generate higher levels of pollution as they lack the modern pollution control technologies. Mineral tailings can degrade over time and release additional PTEs (Mohanty *et al* 2023). Generally, mines in arid and windy regions release higher levels of PTEs due to the lack of humidity and vegetation (Pradhan *et al* 2020). Topography and climatic conditions also impact the emission and distribution of PTEs to the environment

(Mendoza *et al* 2021). Overall, PTEs emissions are influenced by the amount and type of generated mineral waste.

Over the past several years a number of remediation strategies have been developed for the management of mine-contaminated soils (Rajput *et al* 2025). However, several of these strategies have challenges and limitations, notably cost-effectiveness and limited remediation efficacy (Davis *et al* 2021; Dzoujo *et al* 2024; Zeng *et al* 2024). In contrast to traditional remediation strategies, implied chemical and physical techniques, phytoremediation has been accepted as a sustainable, socially and economically viable solution to address PTEs-contaminated environments (Chaudhary *et al* 2024). Phytoremediation utilizes plants to eliminate PTEs in the environment or render them less mobile and harmless through stabilization, filtration, volatilization, or extraction (Erickson and Pidlisnyuk 2021; Ugrina and Jurić 2023). Phytoremediation of mine tailings can be carried out by two primary methods: phytoextraction and phytostabilization (Hassan *et al* 2024). Phytoextraction encompasses the translocation of PTEs from the mine tailings into the aboveground harvestable part of the plant biomass. In contrast, phytostabilization aims to establish a vegetative cover that immobilizes PTEs inside the tailings instead of shooting accumulation (Keith *et al* 2024; Meryeme *et al* 2024).

Biochar, a promising sustainable product of oxygen-free pyrolysis, offers significant potential for supported remediation of polluted soils owing to its environmentally friendly characteristics, compatibility with biological systems, and diverse feedstock possibilities (Pidlisnyuk *et al* 2021; Biney and Gusiatin, 2024; Muema *et al* 2024). Rather often, biochar immobilizes and decreases levels of PTEs and organic contaminants and concomitantly improves soil properties and promotes plant growth (Padhi *et al* 2024). It can be utilized as an organic amendment in mining regions due to its improvement of soil water retention, cation exchange capacity (CEC), available nutrients, metal sorption capacity, and alkaline pH (Ippolito *et al* 2024; Forján *et al* 2024). Recent studies from lead-zinc mining areas confirmed that biochar effectively reduced Pb and Zn mobility, enhanced phytostabilization efficiency, and improved soil physicochemical and microbial properties (Kabiri *et al* 2019; Gao *et al* 2020). Biochar derived from *Miscanthus* × *giganteus* (*M*×*g*) also demonstrated potential to support phytoremediation of Zn and Cu contaminated soils, indicating its applicability for lead-zinc mine restoration (Pidlisnyuk *et al* 2025).

The ecological restoration and reclamation of mining areas have emerged as critical components of sustainable development strategies. In this regard, proper environmental management and planning are essential for preserving biodiversity and mitigating the effects of mining on the surrounding environment (Husain *et al* 2024; Pradhan *et al* 2024). Several research papers have shed light on the importance and effectiveness of the varied phytoremediation strategies for remediating soils contaminated by PTEs. Within this context, lead-zinc mining areas represent one of the most critical cases, as they are characterized by high levels of Pb, Zn, Cd, and Cu, acid-generating tailings, and poor soil fertility, which together create highly challenging conditions for sustainable reclamation. Numerous studies have investigated phytoremediation in lead-zinc mining areas; however, no comprehensive review has yet synthesized and critically assessed these findings to evaluate the effectiveness of different phytoremediation strategies in such environments. This gap highlights the need for assessing environmentally sustainable and economically viable remediation strategies, particularly phytoremediation, suitable for contaminated lead-zinc mining areas. Nevertheless, to the best of our knowledge, this is the first study to review and analyze the published data on the application of phytoremediation and/or assisted phytoremediation strategies to lead-zinc mining areas to mitigate soil PTE contamination. Specifically, this review evaluates (i) conventional phytoremediation using non-native and native plant species, (ii) bioaugmentation-assisted phytoremediation, (iii) phytoremediation supported by arbuscular mycorrhizal fungi (AMF) and earthworms, (iv) plant growth–promoting rhizobacteria (PGPR)–assisted systems, and (v) biochar-assisted phytoremediation, aiming to identify effective practices and highlight research gaps for improving remediation efficiency in Pb–Zn contaminated soils.

2. Method

The review involved a keyword search across two primary academic databases: Web of Science, and Google Scholar, using the following terms: "lead-zinc mine" AND ("heavy metals" OR "potentially toxic elements") AND (phytoremediation* OR remediation*). A total of 181 articles were identified for screening and further analysis, comprising 81 articles from Web of Science and the top 100 publications from Google Scholar.

The search criteria involved the following:

- Studies published in English language
- Studies conducted in the period 2000-2024
- Only peer-reviewed empirical studies
- Empirical studies where phytoremediation was done on a Pb-Zn mining site or done *ex situ* or in a greenhouse with soil collected from a Pb-Zn mining site.

Literature screening involved excluding articles based on their titles, abstracts, full texts, and document types. Specifically, articles with titles indicating the absence of phytoremediation were excluded. When titles were unclear, abstracts were screened, and those indicating no phytoremediation or assisted phytoremediation in sites other than Pb-Zn mining sites were excluded. If the abstracts were still unclear, the full texts were screened, and articles irrelevant to the topic were excluded. Publications such as reviews, books, and other gray literature were excluded. After the thorough screening process, 43 peer-reviewed research articles focusing on phytoremediation in lead-zinc mining areas were selected and evaluated.

Articles evaluated and discussed in this review were separated into three focused topics as shown in Figure 1:

- Phytoremediation: phytoremediation of Pb and Zn with suitable phyto agents,

- Phytoremediation with native plants: phytoremediation potential of plants already growing on Pb-Zn mining sites
- Assisted phytoremediation: including bioaugmentation-assisted phytoremediation, phytoremediation supported by plant growth-promoting bacteria (PGPR), and biochar assisted phytoremediation.

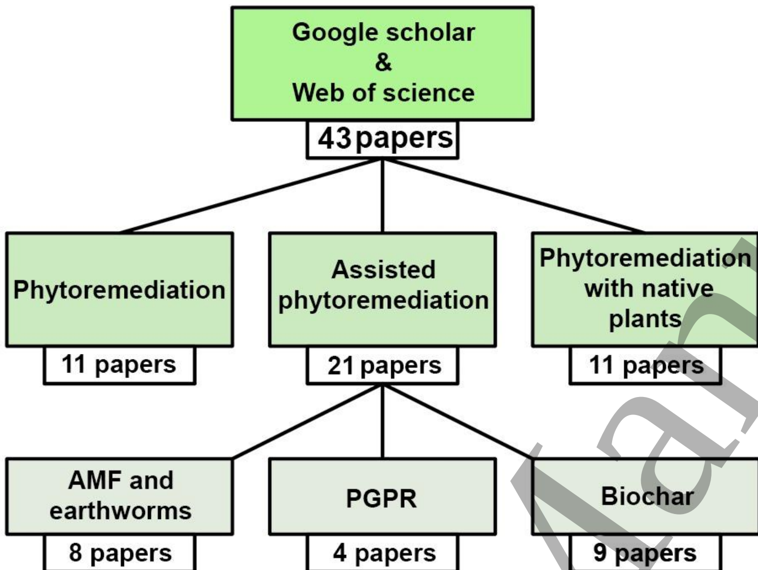

Figure 1. Number of papers selected and reviewed for each topic discussed in the review

3. Lead-zinc mine pollution

Lead and zinc ores are globally distributed mineral resources, and the extraction of these minerals has been an essential component of industry. Globally, at least 226.1 million tonnes of Pb and 610.3 million tonnes of Zn are contained within 851 identified mineral deposits and mine-waste sites across 67 countries, with an average grade of 0.44% Pb and 1.20% Zn (Mudd *et al* 2017). Lead and zinc are primarily utilized in medicine, chemistry, military, electrical, metallurgy, machinery and light industry, making them widely employed non-ferrous metal elements (Nayak *et al* 2022; Qu *et al* 2022). However, the extraction and use of these mineral resources can lead to significant pollution by PTEs in soils at the vicinity of the mining sites (Rouhani *et al* 2025).

Lead-zinc mining has the potential to release and accumulate PTEs in the mining area and the surrounding territories, in particular Pb, Zn, Cu, and Cd, which pose significant ecological and environmental risks (Zhang *et al* 2023; Pan *et al* 2024). The concentrations of these elements in soils from lead-zinc mining areas vary widely worldwide, ranging from 18.49-28,453 mg kg^{-1} for Pb, 30.30-32,287 mg kg^{-1} for Zn, 0.26-191 mg kg^{-1} for Cd, and 0.39-802 mg kg^{-1} for Cu, as reported in the comprehensive global review by Rouhani *et al* (2025), which assessed PTE pollution in lead-zinc mining areas worldwide. Such issues are prevalent across non-ferrous metal mining regions, highlighting the widespread environmental pollution challenge (Cao *et al* 2022; He *et al* 2024). The intensity of impacts resulting from mineral exploitation is influenced by the site characteristics, the volume of material processed, the chemical composition of the ore and adjacent rocks, as well as the extraction methods and technologies employed to mitigate these impacts (Dehkordi *et al* 2024). Furthermore, the process of lead-zinc mining has the potential to enhance mineral weathering (Hower *et al* 2022). The impacts of runoff diffusion and atmospheric sedimentation lead to the accumulation of PTEs within a specific range of soil surrounding the mining area (Csavina *et al* 2012; Zhang and Wang 2020). Consequently, PTEs contents in mining soils are typically elevated compared to background levels (Chrastný *et al* 2015).

Mine wastes and tailings from lead-zinc mining and mineral processing usually have increased concentrations of PTEs, posing considerable environmental and health risks when improperly stored or disposed (Han *et al* 2023; Rouhani *et al* 2025). After mine closure, the runoff and leaching from tailings and waste rocks lead to an increase in the oxidation of residual sulfides, driven by biological, electrochemical, and chemical reactions. Additionally, this process can generate ferric hydroxides and sulfuric acid, resulting in acid mine drainage that boosts the leaching possibility of PTEs and facilitates their movement into soil, surface water and groundwater (Chen *et al* 2023; Rouhani *et al* 2023). Moreover, once the tailings are processed from a solid form into a powdered state, the consequences become more severe since powdered particles are more prone to wind from the tailings dam more intensively over a larger area. Consequently, this broad contamination leads to PTEs entering human, animal and plant food cycles, therefore compromising the health of living entities (Ghazi *et al* 2022).

Once released from lead-zinc mining activities, PTEs discharge into soils, water, and sediments where they persist due to their non-degradable properties. Elevated concentrations of these PTEs in soils and waters have toxicological effects for ecosystems. In soils contaminated with PTEs, these substances disturb soil microbial communities. Metal stress notably decreases microbial biomass and enzyme activities, thus inhibiting essential nutrient cycling and the decomposition of organic matter (Pal *et al* 2022). Such soil contamination also causes phytotoxic effects on plants; for instance, it induces oxidative stress in plant tissues, damaging cells and inhibiting key enzymatic processes in photosynthesis, which leads to inhibited growth and reduced biomass production. Plants grown in metal polluted soil often accumulate these PTEs in roots and shoots, raising concerns about transfer through the food chain and crop contamination (Alengebawy *et al* 2021; Kaur *et al* 2025). In aquatic ecosystems, the toxicity and persistence of PTEs pose serious risks to biota. These metals can bioaccumulate in aquatic organisms. Once inside the organism, they bind to enzymes and other biomolecules, disrupting physiological functions. Effects include inhibited enzymatic activity, organ damage, and impaired nervous and reproductive systems. These can lead to chronic poisoning or death. The exposure to these metals induces genotoxic and reproductive dysfunctions, which consequently lead to diminished reproductive success and a reduction in biodiversity within impacted aquatic ecosystems (Tang *et al* 2023; Sharma *et al* 2025).

Consequently, PTE pollution from lead-zinc mining degrades overall ecosystem health. Soil fertility declines, plant productivity falls, aquatic fauna suffer population losses, and biodiversity is diminished, underscoring the profound long-term ecological impacts of heavy metals released by mining.

4. Phytoremediation

Phytoremediation is a technology that utilizes the ability of plants to absorb PTEs essential for growth, such as Zn, or metals with no known biological function, such as Pb (Erickson and Pidlisnyuk 2021; Bastia *et al* 2023). The careful selection of appropriate phytotechnologies is a pivotal step in the successful remediation of PTE-contaminated sites. For the treatment of mining areas, two primary forms of phytoremediation have been studied: phytoextraction and phytostabilization (Keith *et al* 2024; Hassan *et al* 2024). Phytoextraction utilizes plants to eliminate or decrease metal pollutants detected in mine tailings through accumulating or hyperaccumulating of PTEs in the above-ground biomass. Plants are subsequently harvested and then either combusted for the recovery of metals or disposed of as hazardous wastes (Huslina *et al* 2024). On the other hand, phytostabilization focuses on creating a vegetative cap where sequestration processes such as sorption and binding further immobilize PTEs within the plant rhizosphere. This process effectively reduces metal bioavailability, thereby minimizing related exposure risks (Nsanganwimana *et al* 2021). While plant roots assist in preventing water erosion and leaching, the canopy of a plant helps to mitigate eolian dispersion. Therefore, phytostabilization is a strategy of confinement that involves the creation of a vegetative cap to stabilize the tailings over the long term (Alasmary *et al* 2021; Meryeme *et al* 2024).

Despite the utilization of phytoextraction or phytostabilization, the plants employed should be appropriate and able to tolerate the climatic conditions at the mine tailings site. For example, in warm climates, tailings are usually waterlogged or saturated, requiring the use of plants suited to slightly anaerobic and wetland environments (Craw *et al* 2007; Boi *et al* 2023). In semi-arid and arid climates, it is essential for plants to possess both drought and salt tolerance in order to thrive in dry, and saline tailings environments (Mendez and Maier 2008a; Malunguja and Paschal 2024). Regardless of the phytoremediation strategy, plants having elevated metal tolerance or metallophyte characteristics are commonly selected at most tailing sites. These plants have developed biological mechanisms that enable them to resist and detoxify PTEs. While some of these plants have developed adaptation pathways to tolerate very high PTE contents in shoot and root tissues (hyperaccumulators), others prevent absorbing metal in the rhizosphere or transferring metals into the shoot tissues (Whiting *et al* 2004; Azizi *et al* 2023). Hyperaccumulators have been thoroughly investigated for their ability to significantly accumulate PTEs. Currently, over 500 hyperaccumulator species have been identified globally (Reeves 2024). The proper selection of plant species is an essential factor in phytoremediation technology, as these plants must have suitable properties to thrive in adverse conditions and fulfill the phytoremediation goals (Al Souki *et al* 2020; Liu *et al* 2024). The most suitable plant for phytoremediation has to illustrate rapid growth, high biomass yield, deep root systems, adaptability to poor soil conditions, tolerance to high level of PTEs, and the capacity to accumulate the significant levels of PTEs in harvestable tissues (Chaudhary *et al* 2024).

Numerous studies have tested and identified suitable plants for phytoremediation of lead-zinc mining areas, where some plant species are suitable for phytoextraction (Chehregani *et al* 2009; Ruiz *et al* 2009a; Shi *et al* 2016; Pająk *et al* 2017; Li *et al* 2019) and others work successfully in phytostabilization (Concas *et al* 2015; Ciarkowska *et al* 2017; Shi *et al* 2017; Hesami *et al* 2018; Martínez-Martínez *et al* 2019) based on the ability of plants to accumulate or exclude the Pb or Zn (Table 1).

Table 1. Plant species suitable for phytoremediation of PTEs polluted soils in lead-zinc mining areas

Location (Duration)	Plant species	Pb and Zn concentrations (mg kg^{-1})	Phytotechnology	Conclusions	Reference
		Phytoremediation potential of studied plant species			
Angouran Pb/Zn mine; Iran (field study)	*A. retroflexus*, *P. aviculare*, *G. tournefortii*, *N. mucronata* and *S. orientalis*	Pb: 16700 Zn: 2950	Phytoextraction	*N. mucronata* was the best accumulator for all Pb and Zn	Chehregani *et al* (2009)
Spain (8 weeks)	*Zea mays*; *Helianthus annuus*; *Brassica napus*; *Hordeum vulgare*; *Lupinus albus*	Pb: 127-1652 Zn: 76.2-785	Phytoextraction	PTEs concentration in the test crops followed the order Zn>>Pb > Cu, with maize showing the highest values. Pb was accumulated mainly in the roots of the crops while Zn and Cu were translocated to the aerial parts	Ruiz *et al* (2009a)
Raibl Pb/Zn mining site; Julian Alps, Italy (field study)	*B. laevigata subsp. Laevigata*; *M. Verna*; *T. Rotundifolium subsp. Cepaeifolium*	Pb: 4,782 Zn: 16,930	Phytoextraction	Hyperaccumulation was verified for Pb and Tl in *B. laevigata subsp. Laevigata*, and *M. verna* and *T. rotundifolium subsp. Cepaeifolium* for all PTEs	Fellet *et al* (2012)
Iglesiente District; southwest ern Sardinia, Italy (field study)	*P. lentiscus*	Pb: 2-354 Zn: 48-628	Phytostabilization	The plant is well suited for revegetation actions and could decrease metal mobility	Concas *et al* (2015)
Fuyang city; Southern China (5 months)	*A. fruticosa*; *R. chinensis; L. formosana*	Pb: not given Zn: not given	Phytoextraction	*A. fruticos*a was highly tolerant of PTEs. *R. chinensis* and *L. formosana* had significantly higher translocation factor values for Pb (0.88) and Zn (1.78) than *A. Fruticosa*	Shi *et al* (2016)

Krzeszowice; Poland (29 months)	*Dianthus carthusianorum*; *Biscutella laevigata*	Pb: not given Zn: not given	Phytostabilization	Both species were suitable for the phytostabilization of PTEs	Ciarkowska *et al* (2017)
Southern Poland (field study)	*Pinus sylvestris L.*; *Betula pendula Roth*	Zn not given	Phytoextraction	Zn concentration in the leaves of *Betula pendula Roth* was 4 times greater than in the *Pinus sylvestris L.* needles. The needles and leaves of both plant species accumulated Zn	Pająk *et al* (2017)
Southern China (5 months)	*Q. virginiana*	Pb: not given Zn: not given	Phytostabilization	*Q. virginiana* was metal-tolerant at the seedling state and was a potential candidate for Pb and Zn phytostabilization	Shi *et al* (2017)
Tang-e Douzan mine; Iran (field study)	*C. dichotomum*; *M. neglectum*; *C. falcata*; *O. orthophyllum*; *R. arvensis*; *R. hybrid subsp. Dodecandra*	Pb: 2500 Zn: 1100, 59	Phytostabilization	*C. dichotomum* and *M. neglectum* were effective for phytstabilization of Pb, *C. falcata*, *M. neglectum*, *O. orthophyllum*, and *R. arvensis* for phytostabilization of Zn; *C. falcata*, *M. neglectum*, *O. orthophyllum*, and *R. hybrid subsp. Dodecandra* for phytostabilization of Cd	Hesami *et al* (2018)
Huize County; China (field study)	*A. alpina*	Pb: 547.47 Zn: 4178.24	Phytoextraction	*A. alpina* as a hyperaccumulator, could be used for long-term phytoremediation of PTEs contaminated soils	Li *et al* (2019)
Santa Antonieta mine; Spain (field study)	*Lygeum spartum; Piptatherum miliaceum*	Pb: not given Zn: not given	Phytostabilization	Plants accumulated large concentrations of metals in the roots, with a little translocation to above part biomass	Martínez-Martínez *et al* (2019)

Numerous studies have exhibited the potential of various crop and plant species for phytoextraction and phytostabilization in contaminated lead-zinc mining regions. In Mediterranean mining soils (Spain), for instance, Ruiz *et al* (2009a) reported that several crops, including white lupine (*Lupinus albus*), barley (*Hordeum vulgare*), canola (*Brassica napus*), sunflower (*Helianthus annuus*), and maize (*Zea mays*), showed varying capacities for metal uptake. Among these crops, maize exhibited the highest biomass yield and metal accumulation potential. The concentration of metals in the test crops showed the following order: Zn > Pb > Cu. Pb was mainly concentrated in the root tissues, whereas Zn and Cu were more mobile and transferred to aerial parts, indicating differences in element mobility and plant uptake mechanisms. Notably, in some cases, the concentration of Zn in shoots was up to twice the total concentration of this element in the soil. Further evidence of species-specific accumulation has been reported for hyperaccumulators in another European lead-zinc mining region. Fellet *et al* (2012) confirmed

Thallium hyperaccumulation in *B. laevigata subsp.* and co-accumulation of Pb, Zn, and Tl in *Minuartia verna* and *Thlaspi rotundifolium subsp. Cepaeifolium* at the former Raibl Pb and Zn mining site in the Julian Alps, Italy.

Chehregani *et al* (2009) identified accumulator species (*S. orientalis, N. mucronata, G. tournefortii, P. aviculare,* and *A. retroflexus*) at the Angouran lead-zinc mine (Iran), suggesting their potential for in situ phytostabilization of Pb and Zn. Hesami *et al* (2018) examined 69 plant species from the Tang-e Douzan lead-zinc mine (Iran) for their remediation potential but found none to meet hyperaccumulation criteria, identifying alternatively several tolerant species suitable for phytostabilization, *C. falcata* for Zn and *M. neglectum* and *C. dichotomum* for Pb.

According to Li *et al* (2019), *A. alpina* can be potentially utilized as a hyperaccumulator for long-term phytoremediation of soils polluted with Cd, Pb, and Zn. The authors confirmed the plant's efficiency in long-term phytoremediation experiment utilized in lead-zinc mine area of Huize County, China. *A. fruticosa* showed high tolerance to Zn, Pb and Cu, as reported by Shi *et al* (2016) in a pot experiment aiming to assess the viability of employing transplanted tree seedlings for the phytoremediation of lead/zinc tailings from the Fuyang city (Southern China). It was revealed that the translocation factors for Zn (1.78) and Pb (0.88) were considerably higher in *R. chinensis* and *L. formosana* compared to other species. In another pot experiment from China, Shi *et al* (2017) found that *Q. virginiana* had the highest level of metal tolerance during the seedling stage, making it as a promising candidate for the phytostabilization of Pb/Zn mine tailings.

Concas *et al* (2015) found that *P. lentiscus* in Pb-Zn mining region of the Iglesiente District (Southwestern Sardinia, Italy) exhibited significant tolerance to the high levels of Zn, Pb and Hg. The biological coefficients indicated that this plant relies on an exclusion strategy, characterized by minimal translocation to the above-ground parts, stems and leaves. The authors concluded that *P. lentiscus* was suitable for revegetation efforts and might reduce PTEs mobility via soil stabilization strategies. Martínez-Martínez *et al* (2019) found that *Lygeum spartum* and *Piptatherum miliaceum* effectively phytostabilized Pb, Zn, and As in a tailings pond at the Santa Antonieta mine (Spain) by accumulating significant levels of these elements in the roots, with minimal translocation to aboveground biomass. In Southern Poland, Pająk *et al* (2017) evaluated the accumulative response of silver birch (*Betula pendula* Roth) and Scot's pine (*Pinus sylvestris* L.) to Pb and Zn released by Pb-Zn ore mining. The content of Zn in the leaves of silver birch was fourfold higher than in the needles of Scots pine. Two plant species, *Dianthus carthusianorum* and *Biscutella laevigata*, were shown to be ideal phytoagent for phytostabilization of Zn-Pb post-flotation tailings from the Krzeszowice (SE Poland) over a three-years pot experiment (Ciarkowska *et al* 2017).

$M\times g$ was evaluated by Pavel *et al* (2014) for remediation of Pb–Zn contaminated soils near the Copșa Mică smelter (Romania), where average soil Pb exceeded 680 mg kg^{-1} across a 5000 m^2 site. Low bioconcentration factors (<1) confirmed its excluder characteristic, particularly for Pb, while red mud amendment further reduced Zn and Pb bioavailability. The results suggest that $M\times g$

could be successfully grown on heavily contaminated mining soils contaminated by Zn and Pb and addition of red mud can significantly decrease the concentration of PTEs in the soil and in metal's uptake by plant tissues.

Nevertheless, there are some concerns associated with phytoremediation in certain scenarios. It is noteworthy to mention that the sustainability of phytoremediation depends mainly on how the biomass is managed (Mukherjee *et al* 2025). Inappropriate disposal of the plant residues can affect the soil microbial communities as a result of the pollutants release in bioavailable forms (Khan *et al* 2023). Boucher *et al* (2005) reported the reincorporation of PTEs (Cd and Zn) to the soil in an incubation experiment along with the leaf degradation of Arabidopsis helleri. The secondary contamination could be stemmed from the contaminated plant litter which is considered a potential risk and the increase of soluble PTEs concentrations in the soil due to mineralization (Cao *et al* 2018). Similar results were obtained by Al Souki *et al* (2020), who recorded an increase in the concentrations of mobile PTEs once contaminated miscanthus leaves were incorporated in the soil. On the other hand, this incorporation enhanced the soil organic matter and nutrients as well as supported the microbial populations. The crop residue plays an important role in the enhancement of the soil's organic matter dynamics and nutrient cycling (Medina *et al* 2015).

Another concern of phytoremediation is the consumption of the contaminated biomass by animals. In fact, the plant-animal interactions represent an important energy channel transfers via ecosystems (Banerjee *et al* 2022). Contaminants can be transferred from animal to another food such as meat, milk, eggs, or organs (liver, kidney, and muscles) (Granby *et al* 2012). The consumption of contaminated feed by dairy animals leads to the accumulation of the metals in their tissues, which might be transmitted to the milk (Younus *et al* 2016). According to Kumar *et al* (2018), the high lead absorption in the plant will lead to an increased transfer to the animal consuming them. For instance, Silva *et al* (2025) showed that PTEs were lower in the muscle than in both liver and kidney of beef cattle consuming contaminated plant biomass. The highest concentrations of Se, As, Cd and Hg were found in the kidney. On the other hand, the liver had the highest concentrations of Fe, Mn, Cu, Co, Mo and Ni.

4.1. Native plants

Recently, there has been a growing interest in the utilization of native plants or, at the very least, non-invasive plants to mitigate any adverse impacts on the surrounding ecosystem through introducing of a new plant species to the phytoagents' communities (Thomas *et al* 2022; Phang *et al* 2024; Pandey *et al* 2024). This is of utmost importance when it comes to tailings in areas that are protected and have fragile ecosystems (Rosario *et al* 2007). Furthermore, indigenous plant species that thrive on mine tailings have shown greater adaptability to local conditions, including nutrient deficiencies, pollution, and climate (Malunguja and Paschal 2024). However, successful revegetation of mine spoils often requires an ecologically balanced mixture, combining native stress-tolerant species with selected non-native plants of proven metal tolerance, to accelerate vegetation establishment and ecosystem recovery. Implementation of soil management techniques, primarily through amendments that enhance soil habitability, is also a crucial factor that should be considered when planning the phytoremediation strategy (Bandyopadhyay 2022; Boi *et al* 2023).

Barrutia *et al* (2011) identified *Thlaspi caerulescens* as a Zn-Cd hyperaccumulator in a lead-zinc mine of northern Spain, confirming the species' importance as a dominant accumulator within natural metallophyte communities. Similarly, Wang *et al* (2012) found that *F. buddlejae* thrived in soils severely contaminated with Pb in the Siding lead-zinc mine, with its leaves accumulating Pb at a concentration of 305 $mg.kg^{-1}$, contributing to a balanced community environment alongside other herbaceous plants. Nouri *et al* (2011) discovered that the most efficient species for phytostabilization of Zn were *Scariola orientalis, Echinophora platyloba* and *Centaurea virgata*, and *Scrophularia scoparia* for Pb. The authors confirmed that phytoremediation using native plant species was effective when applied to Pb/Zn contaminated soil. Ha *et al* (2011) evaluated the absorption of metals and metalloids by indigenous plants in a lead–zinc mining region of Northern Vietnam, revealing hyperaccumulation levels ($mg.kg^{-1}$ dry weight) in *P. vittata* (1020), *Potamogeton oxyphyllus Miq.* (4210), and *Ageratum houstonianum Mill.* (1130) for Pb.

In order to evaluate metal-tolerant flora adapted to humid temperate conditions, Monterroso *et al* (2014) examined plant assemblages at a former lead-zinc mine in northwestern Spain. Several populations of *pseudometallophyte* species including *S. atrocinerea, B. celtiberica, C. multiflorum,* and *C. scoparius* were tolerant to the high levels of Pb and Zn despite the unfavorable conditions for plant growth in this area. *Cytisus scoparius* and *C. multiflorus* showed efficacy in Pb and Zn exclusion, making these species the promising candidates for phytostabilization strategies and/or the revegetation of severely polluted mining soils. *Salix atrocinerea* showed notably elevated levels of Zn in its above ground biomass (543 ± 108 $mg.kg^{-1}$) along with a bioconcentration factor reaching 2.35. This plant could offer potential for phytoextraction of soil with low to moderate contamination levels. Fernández *et al* (2017) identified *Coincya monensis* as a Zn hyperaccumulator within the Cantabrian lead-zinc mining belt (northern Spain), further expanding the list of European hyperaccumulators suited for site-specific remediation. The indigenous *Agrostis durieui* was the predominant species at lead-zinc spoil heaps in Carmina, Spain, and it was able to tolerate elevated tissue Pb contents between grass species.

A phytoremediation study using native plants at a lead-zinc mine site in Northern Tunisia revealed that *Rumex bucephalophorus* contained the highest Zn concentration in its shoots (1048 $mg.kg^{-1}$), while *Chrysopogon zizanioides* had the highest Pb concentration in the roots (381 $mg.kg^{-1}$). Although none met phytoextraction criteria, their metal tolerance shows their potential in phytostabilization-based containment of Pb/Zn contaminated soils (Chaabani *et al* 2017).

Lago-Vila *et al* (2019) reported that despite severe Cd, Pb, and Zn contamination in the abandoned Rubiais lead-zinc mine (NW Spain), the pioneer species *Cytisus scoparius* thrived spontaneously and exhibited selective metal accumulation, Zn in roots and shoots and Pb primarily in roots, showing its suitability for stabilization under harsh pedological conditions. Assessment of native vegetation in eastern Morocco revealed that only four of fourteen collected species (*Cistus* *libanotis, Artemisia herba-alba, Stipa tenacissima,* and *Reseda alba*) were Pb hyperaccumulators, while *Stipa tenacissima* and *A. herba-alba* were particularly effective for Zn stabilization (Hasnaoui *et al* 2020). By collecting indigenous plants from a lead-zinc mining area in Inner Mongolia, Wang *et al* (2023) examined their potential for phytoremediation of polluted soils and observed that Chinese cinquefoil herb (*Potentilla chinensis Ser.*) had the capacity to absorb Pb and Zn. In the lead−zinc tailing region of Jiangxi (Southeast China), specific woody plant species showed potential for Pb/Zn remediation (Li *et al* 2023a); specifically, *Paulownia fortunei* was appropriated for Zn remediation. Woody plants are able to absorb higher levels of PTEs compared to herbaceous plants owing to their higher above-ground biomass and well-developed root systems. Cultivation of woody plants showing phytoextraction or phytostabilization properties can restrict the mobility of PTEs and effectively mitigate the migration of soil PTE contamination caused by soil erosion (Laureysens *et al* 2004; Marmiroli *et al* 2011). However, woody hyperaccumulators are influenced by regional conditions, and their ability for phytoremediation is defined essentially by soil conditions (Xiao *et al* 2018). Overall, the identification of native dominating plants that tolerate local soil conditions can improve the remediation efficacy in future phytoremediation endeavors (Heckenroth *et al* 2016; Zhong *et al* 2020).

In lead-zinc mining regions, indigenous plants primarily achieve remediation through phytostabilization instead of phytoextraction. Persistent patterns show Pb accumulated in roots with limited translocation (e.g., *Cytisus scoparius, Chrysopogon zizanioides*), while Zn exhibits greater mobility and above-ground accumulation, enabling rare phytoextraction potential (e.g., *Thlaspi caerulescens, Coincya monensis, Salix atrocinerea*). Pioneer shrubs and xerophytic grasses develop reliable cover on nutrient-poor, metal-rich soils in Spain, Tunisia, and Morocco, where *Cytisus, Stipa tenacissima*, and *Artemisia herba-alba* stabilize contaminated soils and reduce erosion. Woody species (e.g., *Paulownia fortunei*) contribute through high biomass and deep rooting, limiting contaminant migration even when shoot metal concentrations remain below hyperaccumulator thresholds. Notably, several studies (Iran, Morocco, Inner Mongolia) identified few or no authentic hyperaccumulators, highlighting that local tolerance is common but hyperaccumulation is rare and species-specific.

4.2. Bioaugmentation-assisted phytoremediation

The phytoremediation of PTEs in mining areas can face several challenges, such as slow plant growth and limited biomass production, which are often attributed to low soil fertility and the bioavailability of these PTEs in the soil (Nouri *et al* 2011; Geranian *et al* 2013). These challenges are particularly evident in semi-arid and arid soils characterized by limited water availability, low organic matter, and high pH (Mendez and Maier 2008b; Nirola *et al* 2016). To improve the potential for establishment of plantation and address these limitations, the application of biological, organic, or chemical amendments is essential (Mendez and Maier 2008b; Usman and Mohamed 2009; Nurzhanova *et al* 2021). It was revealed that Bioaugmentation-assisted phytoremediation is an effective strategy for the remediation of severely polluted soils (Zhuang *et al* 2007; Lebeau *et al* 2008; Sessitsch *et al* 2013). The application of useful soil organisms, including earthworms, plant growth-promoting rhizobacteria (PGPR), and arbuscular mycorrhizal fungi (AMF), has been proven to promote plant growth and productivity, improve tolerance of plants, and protect plants from the toxicity of PTEs. Additionally, these organisms improve PTEs uptake and bioaccumulation (Ruiz *et al* 2009b; Cabral *et al* 2015; Wang, 2017; Nurzhanova *et al* 2023). As a result, recently published studies have focused on enhancing plant productivity and phytoremediation effectiveness by utilizing bioaugmentation with beneficial soil microorganisms.

Earthworms, AMF and PGPR are crucial soil co-inhabitants that can improve nutrient acquisition and promote plant growth. The combined use of these functionally differing organisms can lead to direct or indirect interactions that positively influence plant productivity and nutrition (Barea *et al* 2005; Frey-Klett *et al* 2007; Wu *et al* 2013) in PTEs polluted soils (Azcón *et al* 2009; Sarathambal *et al* 2017) or metal-free soils (Wu *et al* 2013; Dehghanian *et al* 2018). Earthworms, AMF, and PGPR can interact synergistically to increase PTEs absorption and promote plant growth through several types of strategies, such as inhibition of plant pathogens, higher metal mobilization, and enhanced nutrient acquisition (Aghababaei *et al* 2014; Sarathambal *et al* 2017). Effective phytoremediation of soils contaminated with PTEs depend on the ability of potentially useful soil organisms to colonize the root zone, and, particularly, on their complicated interactions with the metal and plant (Lebeau *et al* 2008; Sessitsch *et al* 2013).

4.2.1. Arbuscular mycorrhizal fungi and earthworms

Ma *et al* (2003) revealed, in a pot experiment with *Leucaena leucocephala* grown on lead-zinc mine tailings, that inoculation with the earthworm *Pheretima guillelmi* significantly improved plant growth when tailings were amended with 25% unpolluted soil. Earthworm activity enhanced phosphate availability, enhanced microbial processes, and increased metal bioavailability, leading to a 53% rise in total metal uptake. In a subsequent greenhouse study, Ma *et al* (2006) evaluated the combined influence of *Glomus spp.* (AMF) and *P. guillelmi* on *L. leucocephala* grown on amended lead-zinc tailings. The influence of AMF on metal uptake surpassed that of earthworms; however, their combined effect resulted in a reduction of Pb and Zn mobility in soil by up to 25%. Furthermore, minor yet substantial negative interactions were detected; for instance, earthworms increased soil microbial activity but diminished the positive impact of AMF on nitrogen fixation.

Wu *et al* (2010) conducted a field experiment on lead-zinc mine tailings to evaluate the impact of waste compost and AMF on phytoremediation utilizing vetiver grass slips. The incorporation of waste compost yielded three times more biomass than the untreated control, mostly due to improved soil characteristics and higher nutrient availability compared to control. The contents of nitrogen and phosphorus in the shoots were considerably elevated in mycorrhizal treatments compared to those lacking AMF inoculation. Furthermore, application of AMF led to a notable reduction in content of PTEs within the roots, while the levels in the shoots remained unchanged.

While examining the community structure of AMF associated with *Veronica rechingeri* at the Anguran zinc-lead mining area (Iran), Zarei *et al* (2008) used molecular characterization to reveal that AMF diversity, colonization rates, and spore density declined with increasing PTE concentrations in soils. Specific AMF sequence types persisted even in zones of extreme contamination, suggesting the existence of highly metal-tolerant AMF ecotypes. A greenhouse experiment by Solís-Domínguez *et al* 2010 evaluated AMF effects on rhizosphere microbial dynamics and growth of the native legume *Prosopis juliflora* in acidic lead-zinc tailings. AMF inoculation modified bacterial and fungal community composition and increased biomass, while shoot metal concentrations remained below US toxicity thresholds (National Research Council, 2005). These results indicate that AMF indirectly enhance phytostabilization by improving rhizosphere function rather than promoting metal translocation

Gu *et al* (2017) indicated that inoculation of four plant species with the AMF *F. mosseae* effectively promoted phytostabilization in the Guojiatun lead-zinc tailings (North China) through promoting plant growth and reducing the accumulation and migration of PTEs within plants' biomass. Inoculation of mycorrhiza led to a substantial rise in plant biomass for *T. pallida, H. spectabile* and *F. arundinacea*, as well as decreasing PTEs accumulation and migration into shoots by immobilizing them within the root system. Zhan *et al* (2019) further confirmed, through a pot experiment with *Cynodon dactylon* on lead-zinc mine waste soils, that AMF inoculation increased soil pH, enhanced P and S absorption, and improved overall plant nutrition. It also resulted in decreasing the levels of available Pb and Zn in the soils, and concentration of Pb in shoots. The translocation factor (TF) and translocation capacity factor (TF') of Pb and Cd in Bermudagrass reduced, while the TF and TF' of Zn increased.

Across lead-zinc mine soils, AMF and earthworms mainly promote phytostabilization rather than phytoextraction. Their presence enhances plant growth by improving soil fertility, increasing available phosphorus, and, in the case of AMF, raising soil pH and nutrient uptake. When combined, AMF and earthworms can reduce metal mobility in soil, as shown by Ma et al. (2006), where Pb and Zn mobility decreased by about 25%. However, minor negative interactions, such as reduced nitrogen fixation, may occur. The influence of AMF on elemental distribution varies. In some cases, Pb transport to shoots decreases, while Zn mobility may remain stable or even increase. AMF diversity and colonization decline with higher contamination, but metal-tolerant strains persist and maintain cooperative benefits.

4.2.2. Plant growth-promoting rhizobacteria

Sharma *et al* (2019) showed that the inoculation of the endophytic community considerably improved the growth of *Arabis alpina* in a multi-metals stress conditions at a lead-zinc mining site in Southwest China. Inoculation of the endophytic community significantly modified the contents of Pb, Cd, and Zn in plant tissues. In addition, it significantly reduced the levels of Pb ($p<0.05$) and Cd ($p>0.05$) in shoots. Endophytes are microorganisms living within the internal tissues of host plants, exhibiting no symptoms of disease. In this mutually beneficial relationship, the host plant permits the endophyte to live and multiply within its tissues, while the endophyte offers several benefits to the plant, such as enhancing its tolerance to both biotic and abiotic stresses

(Waller *et al* 2005; Shahzad *et al* 2017). Endophytes are widely distributed in metal-polluted environments, and some types can enhance the tolerance of host plants to PTEs and increase plants' metal absorption potential (Deng *et al* 2011; Yamaji *et al* 2016). For this purpose, they detoxify PTEs, modify metal distribution in plant cells and improve antioxidative systems, etc. (Wang *et al* 2016).

Tang *et al* (2019) investigated the influence of peat amendment on Pb and Zn stabilization in tailing soils from Southern China. Several tolerant species, including *Sapium wilsoniana, Sapium sebiferum, Salix matsudana, Ricinus communis, Populus nigra, Hibiscus cannabinus,* and *Corchorus capsularis*, exhibited strong metal tolerance and stabilization capacity. A 10% peat amendment produced the most effective Pb and Zn immobilization in the rhizosphere compared with both 20% peat and untreated control soils. Similarly, Zhang *et al* (2019) observed that *Paulownia fortunei* cultivated in lead-zinc slag with peat amendments accumulated increasing levels of Cd, Cu, Zn, and Pb with rising peat amounts. The 30% peat treatment resulted in the highest metal accumulation in plant tissues, suggesting that organic amendments enhance metal mobility and root uptake.

Two PTE-tolerant PGPRs, *Agrobacterium radiobacter* and *Mesorhizobium loti*, enhanced the phytoremediation potential of *Robinia pseudoacacia* in a lead-zinc mining area in China (Fan *et al* 2018). These two isolates impacted the overall absorption of PTEs in the *R. pseudoacacia*, either negatively or positively, based on the content and type of the added PTEs. In Central Iran, native *Scorzonera inflata* exhibited strong tolerance to Pb and Zn in contaminated soils from the Bama lead-zinc mine. Mahohi and Raiesi (2019) reported that application with metal-resistant earthworms and PGPR enhanced the mobility and bioavailability of Pb and Zn, facilitating their transfer through mycorrhizal hyphae and subsequent plant uptake, thereby improving the overall remediation process. In a lead-zinc mining region in Huayuan County, China, Xiao *et al* (2023) examined the assistance potential of the rhizosphere bacterial community to facilitate the phytoremediation process with different species. *Artemisia argyi* showed a tendency to accumulate Cd, *Boehmeria nivea* accumulated Cr and Sb, and *Miscanthus floridulus* accumulated Cr and Ni. In addition, *Cyanobacteria/Chloroplast*, *Acidobacteria* and *Chloroflexi* effectively adsorbed PTEs. Authors found a strongly positive correlation ($p<0.05$) between translocation factor of Cd, Cu, Mn, Pb and Zn and the dominating phylum *Cyanobacteria/Chloroplast* in *Boehmeria nivea*.

In lead-zinc contaminated soils, studies commonly show that PGPR and endophytic microbes enhance plant growth under metal stress, while their effects on metal response vary with microbial associations and amendments. PGPR can either stabilize or mobilize metals depending on the species involved and the amendment. Reduced peat amendments have enhanced phytostabilization in tailings, while elevated levels have led to increased metal uptake and accumulation in certain plant hosts. Similarly, the inoculation of PGPR and earthworms has enhanced soil-metal mobility and plant uptake. Community-level analyses indicate that certain taxa (e.g., Cyanobacteria/Chloroplast) are associated with higher metal translocation metrics in specific plant-site contexts.

4.3 Biochar assisted phytoremediation

Biochar is a by-product rich in carbon that is generated through the pyrolysis of biomass under conditions of limited oxygen concentration. Beneficial characteristics of biochar, such as porosity, diverse functional groups, high surface area, and capacity for adsorbing organic and inorganic contaminants, have improved its efficacy in mitigating environmental pollutants (Pidlisnyuk *et al* 2021; Tan and Yu 2024). The feedstock characteristics and pyrolysis conditions primarily determine the physical and chemical properties of biochar. The temperature is a crucial factor in the generation of biochar during pyrolysis (Gusiatin and Rouhani 2023). The utilization of biochar for in situ remediation of PTEs is an attractive option owing to its cost-effectiveness, especially when generated from organic biomass that would otherwise be discarded. Additionally, its relative environmental stability may facilitate long-term PTE immobilization in comparison to other organic compounds (Biney and Gusiatin 2024; Muema *et al* 2024).

The main processes by which biochar immobilizes PTEs in soils involve raising soil pH, facilitating ion exchange, enabling physical sorption, and promoting precipitation as oxi-hydroxides, along with carbonate or phosphate (Ghorbani and Amirahmadi 2024). The impact of biochar remediation on soil in mining areas is influenced by the mining environment, the soil conditions, the physicochemical properties of biochar, and the method of application. These factors can result in significant variations in the remediation effectiveness of biochar supported phytoremediation within various mining areas. Therefore, it is essential to establish standardized protocols for the use of biochar remediation in mining soil (Gao *et al* 2022).

Metal immobilization and reduced bioavailability in soil amended with biochar occur through several mechanisms, such as: (i) adsorption and complexation: biochar has a porous structure with a high surface area and a rich variety of surface functional groups, such as hydroxyl, carboxyl, and phenolic groups. These characteristics allow biochar to effectively adsorb and complex metal ions like Pb and Zn, binding them to its surface and reducing their mobility and bioavailability in soil (Anawar *et al* 2015; Jun *et al* 2020; Alhar *et al* 2021); (ii) pH adjustment: biochar application generally raises soil pH, especially in acidic soils, by releasing alkaline substances like calcium, potassium, and magnesium. Metals, such as Pb and Cd, can decrease solubility at higher pH levels. Consequently, the metals precipitate as less soluble compounds, becoming immobilized and thus less accessible to plants and soil organisms (de Souza *et al* 2019; Lebrun *et al* 2021a; Lebrun *et al* 2021b); (iii) surface precipitation and mineral transformation: biochar can facilitate the transformation of metals into stable mineral forms. For example, metals in the rhizosphere area can precipitate as carbonates or oxides when biochar is present, forming mineral phases that are less soluble and toxic. This further reduces metal leaching and transport, stabilizing PTEs within the soil (Gascó *et al* 2019; Benhabylès *et al* 2020).

Biochar amendments benefit soil quality, particularly in degraded mining soils, by enhancing the structure, nutrient content, and microbial activity. It enhances soil aggregation, water retention, and porosity, thereby improving aeration and reducing compaction. Mining soils are often compacted and low in organic matter, limiting root penetration and water movement. Biochar helps to create a more porous and aerated structure, which improves root growth, water infiltration, and reduced surface runoff (Nandillon *et al* 2019; Gusmini *et al* 2021). Biochar also enhances the soil's cation exchange capacity (CEC), reducing nutrient leaching and increasing the availability of essential elements such as nitrogen and phosphorus, which in turn promotes plant growth and phytoremediation efficiency (Gascó *et al* 2019; Lebrun *et al* 2021a). Moreover, biochar creates a favorable habitat for microbial communities that assist in bioremediation. Its porous structure provides shelter for soil microbes, including those involved in nutrient cycling and metal transformation. These microbes can promote metal immobilization through biological processes such as microbial precipitation, further stabilizing PTEs in the soil (Anawar *et al* 2015; Lebrun *et al* 2021a).

Successful phytoremediation depends on plant growth and biomass, as larger plants can uptake and immobilize more contaminants. Biochar contributes to these aims mainly through process: (i) reducing metal toxicity and by immobilizing metals and reducing their bioavailability. This protects plants from metal toxicity, which can otherwise inhibit plant growth and root development. This reduction allows plants to thrive in contaminated soils, generating more biomass and thus improving their capacity for contaminant uptake and stabilization (de Souza *et al* 2019; Gusmini *et al* 2021). (ii) stimulation of root growth: moreover, biochar increases root biomass and root length, enhancing the plant's capacity to explore and remediate more soil. With more extensive root systems, plants can more effectively immobilize metals in the rhizosphere (root zone), where biochar can adsorb and stabilize metals (Nandillon *et al* 2019; Lebrun *et al* 2021a). (iii) increased plant uptake and translocation factors: for phytoextraction purposes, biochar has been shown to enhance the uptake of metals such as Cd and Pb in some hyperaccumulator plants. Enhanced root-to-shoot translocation is beneficial in phytoextraction, where contaminants need to be transported to aboveground biomass for potential harvest and removal. However, in phytostabilization, the reduction of translocation factors (TF) due to biochar is favorable as it keeps contaminants in the roots, preventing them from reaching edible or aerial parts of the plants (Gascó *et al* 2019; Alhar *et al* 2021).

Biochar aids phytostabilization by facilitating the establishment of a vegetation cover that can contain and immobilize contaminants within the rhizosphere. By providing an ideal environment for root growth and stability, biochar helps to contain contaminants within the rhizosphere, where they are less likely to migrate or leach into surrounding areas. This containment is critical in preventing off-site contamination from abandoned mining areas (Benhabylès *et al* 2020). Biochar's presence in the rhizosphere can enhance PTEs complexation in root-adjacent soil, allowing plants to sequester contaminants without transporting them into the aerial parts of the plant (Nandillon *et al* 2019; Lebrun *et al* 2021a).

Examples of biochar-assisted phytoremediation in mining affected soils from various global regions are summarized in Table 2, while the principal mechanisms and benefits are illustrated in Figure 2.

Table 2. Examples of biochar-assisted phytoremediation in multi-metal contaminated soils in mining areas from different regions

Study area	Biochar type	PTEs	Soil pH improvement	PTE reduction in soil (%)	Increase in plant biomass (%)	References
Orléans, France	Biochar and compost	Pb As	Not specified	Reduced bioavailability of Pb and As in soil	Enhanced growth (*Oxalis pescaprae*)	Benhabylès *et al* (2020)
Shuikoushan, China	Lychee biochar	Pb Cd Zn As	+0.3–0.6 pH unit	Pb: 12.4%, Cd: 11.0%, As: 4.35%	22.9–58.9% (Sunflower)	Liu *et al* (2020)
Riotinto, Spain	Manure biochar	Pb Zn As	+0.5–1.0 pH unit	Pb: 40–60%, Zn: 25–50%	30–50% (*Brassica napus*)	Gascó *et al* (2019)
Pará, Brazil	Açaí biochar	Pb Ni Ba	+0.4 pH unit	Pb: 20–40%, Ni: 30–50%	15–35% (Lettuce)	de Souza *et al* (2019)
Orléans, France	Mixed biochar and compost	Pb As	+1.2–1.5 pH unit	Pb: 70–90%, As: 50–75%	40–60% (Poplar)	Nandillon *et al* (2019)

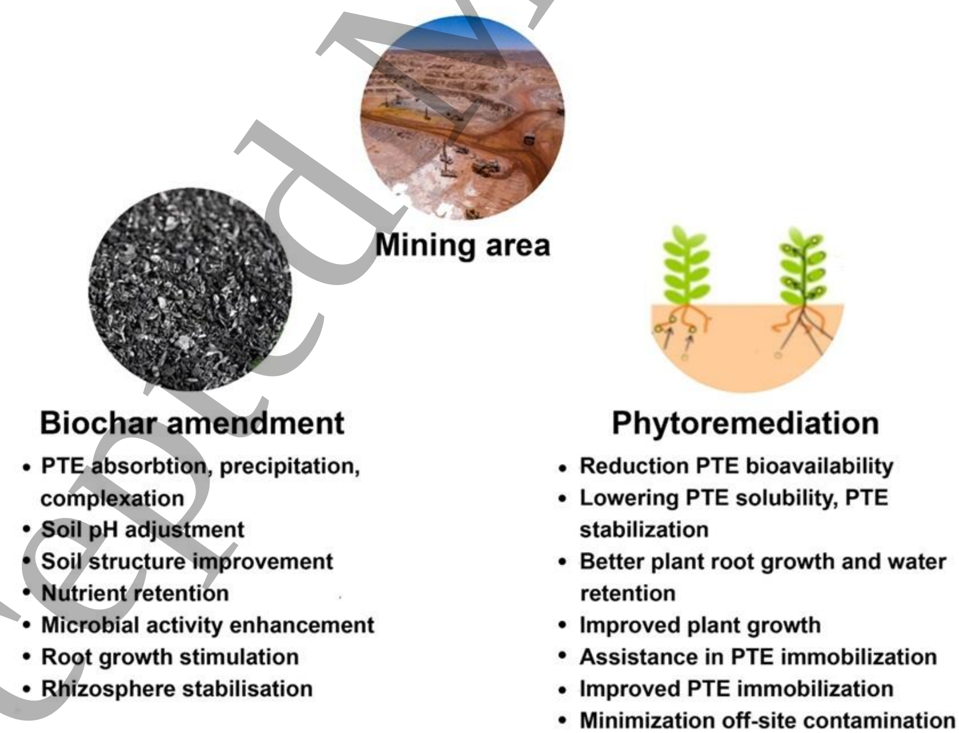

Figure 2. Summary of the main benefits of phytoremediation and biochar application to the mining area

Numerous studies have revealed that biochar application effectively mitigates the mobility and bioavailability of PTEs, particularly Pb, Zn, and Cd, which are major pollutants in Pb-Zn mining regions. Kabiri *et al* (2019) conducted one of the earliest assessments of biochar-assisted phytoremediation in lead-zinc mining soils, studying the impact of walnut leaves biochar on the fractionation and phytotoxicity of Pb and Zn in naturally calcareous and heavily contaminated soil within the Bama lead-zinc mine site. They found that biochar effectively decreased Zn and Pb levels in plant tissues and improved maize growth performance by altering the fractions of these metals. Moreover, Zn and Pb were fractioned by biochar from easily accessible forms (soluble, exchangeable, coupled with carbonates, coupled to Fe-Mn oxides) to less available partitions (associated with organic matter and residual), indicating the stabilization of metals and reduced environmental risk. Using a pot experiment, Gao *et al* (2020) further evaluated the combined effects of biochar and other organic amendments (biochar, peat, manure, and non-contaminated soil) on aided phytostabilization using king grass (*Pennisetum purpureum* × *P. thyphoideum*) in mine tailings. Biochar had a higher immobilization capacity for Cd, Pb, Zn, and As compared to other amendments. The combination of all four amendments showed the least amount of metal uptake into the king grass and the most reduction in metal leaching. Notably, the plant was able to survive even in unamended tailings, but biochar-rich mixtures significantly enhanced biomass and physiological vitality, showing the potential of this approach for *in-situ* immobilization of PTEs in Cd and Pb contaminated tailings.

Li *et al* (2023b) studied effectiveness of sewage sludge biochar amendment with *Boehmeria nivea L.* in improving physicochemical properties and rehabilitating microbial communities in lead-zinc mine tailings pond of Meizhou (China). They demonstrated that biochar amendment could directly immobilize PTEs through chemical reaction and indirectly stabilize them via phytostabilization, thereby improving soil pH, TC and TN content. The amendment also enhanced beneficial soil microbiota, particularly nitrogen-fixing bacteria such as *Mesorhizobium, Bradyrhizobium*, and *Rhizobium*, which improved plant growth and contributed to soil rehabilitation. Biochar amendment, particularly non-woody sewage sludge biochar, obtained a higher comprehensive performance score (3.1-3.6) compared with woody biochar, highlighting the influence of feedstock type on remediation efficiency. These results show that the synergy between biochar and appropriate plant species can improve microbial function and vegetation establishment in contaminated tailings. In contrast, woody biochar applied with *Amorpha fruticosa* did not show significant positive effects on the phytostabilization of lead-zinc tailings (Sikdar *et al* 2020).

Recent research has also examined the use of biochar derived from energy crops for circular remediation strategies. Biochar derived from *M*×*g* roots cultivated long-term in slightly contaminated soil was tested in biochar supported phytoremediation experiment using Cu or Zn spiked soils (Pidlisnyuk *et al* 2025). Two biochar doses (1.67 and 5.00%) were evaluated with varying levels of Cu (200 to 416 $mg.kg^{-1}$) or Zn (202 to 580 $mg.kg^{-1}$) concentrations. The study revealed a beneficial influence of biochar on plant's development; specifically, plant height and aboveground biomass increased by 20.4 and 115%, respectively, for biochar's supported process compared with the control. Moreover, improvements were observed in key phytoremediation metrics such as tolerance index, bioconcentration factor, translocation factor, and the comprehensive bioconcentration index, confirming the suitability of $M \times g$ biochar for sustainable post-remediation management. The results also suggested a potential for valorizing contaminated biochar in subsequent remediation cycles, providing a sustainable approach to waste utilization.

The studies conducted in lead-zinc mining soils and related contaminated materials showed that biochar-assisted phytoremediation can effectively reduce the mobility and bioavailability of PTEs such as Pb, Zn, and Cd. Biochar also improves soil physicochemical properties, including pH and nutrient content, and enhances microbial community structure, particularly by promoting nitrogen-fixing bacteria. These improvements facilitate vegetation establishment and greater plant biomass, as observed for species such as king grass and $M \times g$ (Gao *et al*, 2020; Pidlisnyuk *et al*, 2025). However, biochar effectiveness is influenced by multiple variables, varying with feedstock type, application rate, plant species, and substrate characteristics, as shown by the limited benefits of woody biochar with *Amorpha fruticosa*. In summary, the mechanisms underlying the positive outcomes of biochar application involve pH-driven precipitation and adsorption complexation processes. Along with these, rhizosphere improvements enhance plant and microbial functioning. These factors contribute to more stable and sustainable remediation in lead-zinc mining areas.

5. Conclusion and future perspectives

Lead-zinc mining activities cause long-term soil degradation and accumulation of PTEs, particularly Pb, Zn, Cd, and Cu, which degrade soil quality and pose environmental risks. This review critically synthesized two decades of studies on phytoremediation and assisted phytoremediation in lead-zinc mining areas worldwide, focusing on the effectiveness of various plant-based and amendment-supported strategies. The findings revealed that phytostabilization is the primary remediation pathway, as Pb was largely immobilized in roots, while Zn showed limited but species-specific phytoextraction potential. Native and tolerant species, including *Cytisus scoparius, Stipa tenacissima,* and *Artemisia herba-alba*, effectively developed vegetation cover and reduced metal mobility, whereas deep-rooted woody plants contributed to long-term stabilization. Assisted approaches using AMF, PGPR, earthworms, and biochar consistently improved soil structure, fertility, and microbial activity while reducing PTE bioavailability. Combining tolerant vegetation with targeted biological or organic amendments offers the most sustainable remediation strategy for lead-zinc mine impacted soils.

The received outcomes and conclusions permitted to improve the scientific knowledge and prognosis concerning PTEs remediation perspectives in the soil mining sector. Further studies are requested to broaden and fortify the expertise on managing lead-zinc soil contamination without jeopardizing human and environmental health. Therefore, the following suggestions have to be taken into account for upcoming studies on effective soil remediation strategies in lead-zinc mining areas and the adjacent environments:

a) Numerous studies have reported the suitability of remediation strategies, specifically application of phytoremediation and/or assisted phytoremediation toward PTEs treatment in the lead-zinc mining areas. However, there is a lack of comprehensive knowledge on the processes that control phytotoxicity, availability, and redistribution of PTEs in such soils. Therefore, future studies should concentrate on field-scale experiments to assess the earlier developed remedial procedures, taking into consideration the associated human health effects.
b) The utilization of biochar in assisted mining soil remediation has been gaining an increased popularity. Nevertheless, the efficiency of the approach is defined by several factors. For instance, biochar structure has to be modified chemically and physically creating biochar-based composites or hybrid materials. The modifications may influence the application dose and eventually strengthen the success of the remediation process. The modified biochar applications should be deeply evaluated and practically targeted to remediate lead-zinc mining areas.
c) The impact of remediation strategies can be better understood by investigation of chemical, physical and biological characteristics of the rhizosphere soil. Currently, only a few studies have examined the alterations in these parameters along with the geochemical fractions of PTEs in rhizosphere soil amended by biochar. It is essential to examine the impact of biochar on the rhizosphere soil s in respect of PTEs speciation and mobility.
d) The restoration of the ecosystems in the tailing areas depends heavily on the state of the microbial communities. However, still there is a limited knowledge on the potential of pioneer vegetation and rhizosphere soil cover in improving function and structure of microbial communities in adjacent tailings. Thus, future studies have to investigate the physical-chemical properties of tailings, plant colonization development, changing of microbial communities, enzymatic activities and functional genes in the tailing area.
e) Finally, taking into consideration that phytoremediation technology is a relatively new process proposed to PTEs mining areas, there is a scarcity of information concerning its long-term effects of the utilized in lead-zinc mine soils. The multiyear monitoring and data recording is recommended for further successful implementation of PTEs remediating technique applied to mining areas.

Future investigations in lead-zinc mining phytoremediation should be directed towards the development of sustainable and field strategies ensuring the long-term stability and safety of the soil's remediation. The major challenges that need more attention is the sustainable management of plant biomass generated after phytoremediation. To prevent the secondary contamination from the contaminated biomass, the future research could explore environmentally approaches. Moreover, the sites were phytoremediation is applied require further attention to prevent secondary contamination. Safe thresholds for land reuse, grazing and biomass by-product should be determined, due to the food safety risk assessment. These future directions will assist to strengthening the scientific aspects and practical of phytoremediation as a sustainable solution for the reclamation of lead zinc mining areas.

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