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Phytoremediation as a Strategic Alliance Between Nature and Mining for a More Sustainable Future: a Literature Review

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This review synthesizes evidence from 60 articles (2019–2023) on phytoremediation of mining-contaminated soils identified through searches in Scopus and Web of Science. Screening followed PRISMA principles. Five themes were analyzed: (i) phytotechnology in contaminated soils, (ii) phytotechnology forms, (iii) assisted phytoremediation, (iv) effectiveness, and (v) plant-based applications. Across the included studies, evidence highlight the effectiveness of specific plant species and the use of plant growth-promoting bacteria (PGPB) and other amendments to accelerate metal removal; however, success depends on plant adaptability, accurate contaminant identification, and feasible remediation timeframes. Evidence is dominated by laboratory/greenhouse designs, with comparatively few field-scale validations. We recommend expanding real-scale trials, comparing species and amendments under diverse edaphoclimatic conditions, and deepening research on plant–microorganism interactions, alongside standardized monitoring protocols and multidisciplinary collaboration to optimize practical deployment of phytoremediation in mining soils.

1. Introduction

Mining is one of the primary activities driving Peru's economic and industrial development 21 Cruzado-Tafur et al., 2021; Reboredo et al., 2021), yet its expansion can affect natural vegetation and trigger persistent environmental impacts linked to heavy metals (Madejón et al., 2022; Wu et al., 2021). These contaminants degrade soils, water and crops and pose risks to human health (Heredia *et al.*, 2022; Zheng *et al.*, 2022), underscoring the need for effective remediation strategies.

Remediation approaches include physical, chemical and biological methods (Gascó *et al.*, 2019; Ortúzar *et al.*, 2020; Liu *et al.*, 2021; Wu *et al.*, 2021). Conventional options such as vitrification, electrokinetics and soil washing, can be viable (Heredia *et al.*, 2022) but are often costly, may leave persistent residues and can irreversibly alter soil properties (Wu *et al.*, 2021; Singh, Singh and Dhal, 2022). In recent years, more sustainable and cost-effective alternatives have gained traction (Gascó *et al.*, 2019), with phytoremediation standing out.

Phytoremediation relies on plant capacities to absorb, transfer, stabilize, concentrate and/or degrade contaminants (Pusz, Wiśniewska and Rogalski, 2021; Heredia *et al.*, 2022), helping to reduce erosion and leaching while contributing to soil fertility (Pandey *et al.*, 2021). It is widely regarded as a strategic, cost-effective and environmentally sustainable measure applicable to various contaminants (Cruzado-Tafur *et al.*, 2021; Opeña *et al.*, 2022). Nonetheless, its performance depends on (i) plant adaptability, (ii) accurate contaminant identification and (iii) the time required for remediation (Pandey *et al.*, 2021), and it can be enhanced with supporting inputs such as plant growth–promoting bacteria, compost or manure.

In this context, the present review analyses and synthesizes evidence on the efficiency of phytoremediation for removing heavy metals from mining soils, drawing on articles published between 2019 and 2023 in Scopus and Web of Science. The research question guiding this work is: What are the most used elements in phytoremediation that have demonstrated the highest effectiveness in the removal of heavy metals according to the existing literature? This approach allows the identification of patterns and knowledge gaps to orient future applications and research.

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2. Methodology

We conducted a literature review of primary research articles addressing “phytoremediation” and “mining”. Searches were run in Scopus and Web of Science for publications between 2019 and June 2023, targeting records that included “phytoremediation” and “contaminated soils” in the title, abstract, or keywords. Screening followed PRISMA 2020 principles. From 118 records identified (all in Scopus; no results in Web of Science), three screening criteria were applied: duplication, title relevance, and abstract relevance. Title screening retained all 118 records. Abstract screening excluded 57 articles due to incompatibility with the study objective (n = 43), absence of phytoremediation (n = 2), exclusive focus on soil, water, or other elements unrelated to phytoremediation (n = 8), or a purely chemical scope (n = 4), yielding 61 eligible articles. Full-text assessment excluded one study (Li et al., 2020) because it is a prior systematic review; it was kept as a background reference. Finally, 60 articles were included for qualitative synthesis and full-text analysis.

3. Results

Given the importance of phytoremediation as a sustainable strategy for mitigating heavy metal pollution in mining areas, this study used a systematic approach to identify the main research topics and the most notable contributions in this field, creating two figures, one showing the thematic distribution of the 60 articles analyzed and the other showing the 88 proposals and/or contributions extracted from the documents analyzed. Both visual resources serve as a starting point for presenting the key results of this work.

3.1 Main Research Topics on Phytoremediation in Mining

Across the 60 studies, five research topics were identified (Figure 1). In phytotechnology in contaminated soils (n = 5), evidence covers: afforestation trials on legacy coal-mine soils contaminated with Zn, Cd, Mn, Pb and Cu (Lan *et al.*, 2020); endophytic Micromonospora producing metallophores for bacterial-assisted bioremediation (Ortúzar *et al.*, 2020); plant growth-promoting bacteria applied in Cd-contaminated mining areas (Liu *et al.*, 2021); cowpea genotypes tested in Hg-contaminated soils (Marrugo-Negrete *et al.*, 2020); and manure-derived hydrochars/biochar evaluated for heavy-metal removal (Cárdenas-Aguiar *et al.*, 2020).

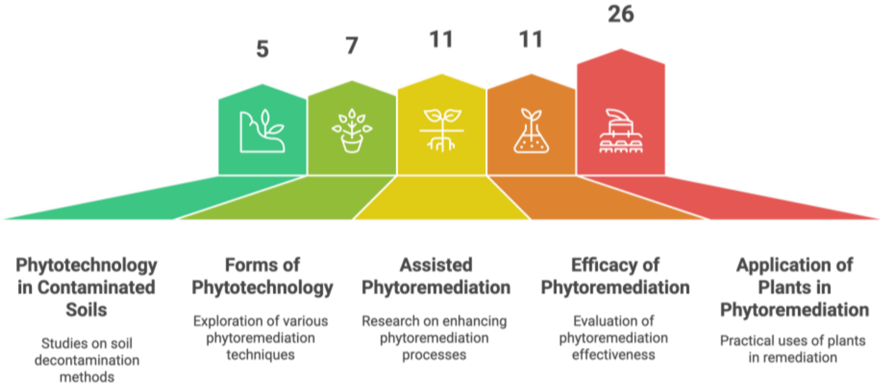

Figure 1. Grouping of Research Topics on Phytoremediation in Mining.

In forms of phytotechnology (n = 7), studies address microalgae for bioremediation (Vela-García, Guamán-Burneo and González-Romero, 2019); rhizobacteria-tolerant plants applied to phytoremediation (Madline, Benidire and Boularbah, 2021); rhizosphere microbiomes under Hg/Cd contamination (Saldarriaga *et al.*, 2023); mercury-resistant biofilm bacteria with local plants (Nurfitriani, Arisoesilaningsih and Nuraini, 2023); simultaneous application of clay minerals (Otunola *et al.*, 2023); incorporation of low-molecular-weight organic acids (Zheng *et al.*, 2022); and tilapia growth as a phytoremediation approach (Maharani *et al.*, 2022).

In assisted phytoremediation (n = 11), three lines are distinguished: amendments applied and evaluated within aided phytoremediation (Simiele *et al.*, 2020; Lebrun *et al.*, 2021; Pandey *et al.*, 2021; Pérez *et al.*, 2021; Shahrokh *et al.*, 2023); heavy-metal behaviour determined in amended mining soils (Nandillon *et al.*, 2019; Norini *et al.*, 2019; Baragaño, Gallego and Forján, 2021; Madejón *et al.*, 2022); and biochar effects investigated as a remediation tool (Gascó *et al.*, 2019; Alhar, Thompson and Oliver, 2021).

In efficacy of phytoremediation (n = 11), the first group tests vegetation and/or biochar in contaminated soils (Benidire *et al.*, 2021; Štofejová, Fazekaš and Fazekašová, 2021; Wu *et al.*, 2021; Singh, Singh and Dhal, 2022); the second analyses comparative strategies for heavy-metal removal in mining areas (Lebrun *et al.*, 2021; Bhat *et al.*, 2022; Bortnikova *et al.*, 2022; Matei *et al.*, 2022; Singh, Singh and Dhal, 2022); and the third evaluates species-level efficacy in mining-derived substrates (Opeña *et al.*, 2022; Zhenggang *et al.*, 2022; Watts *et al.*, 2023).

Finally, in application of plants in phytoremediation (n = 26), four strands appear: use of native/dominant species in mining-contaminated soils (Chen *et al.*, 2019; Vela-García, Guamán-Burneo and González-Romero, 2019; Cai *et al.*, 2020; Hasnaoui *et al.*, 2020; Pidlisnyuk *et al.*, 2020; Shi, Veiga and Anderson, 2020; Băbău *et al.*, 2021; Petrović *et al.*, 2021; Pusz, Wiśniewska and Rogalski, 2021; Reboredo *et al.*, 2021; Wang *et al.*, 2022; Wibowo *et al.*, 2022); assessments of plant capacity within phytoremediation (Cai et al., 2021; Cruzado-Tafur et al., 2021; Desai et al., 2019; Heredia et al., 2022; R. Li et al., 2020; Li et al., 2019); comparative effects of different plants in contaminated soils (Garau *et al.*, 2021; Matanzas *et al.*, 2021; Webber *et al.*, 2021; Berkaoui *et al.*, 2022; Durante-Yánez *et al.*, 2022); and identification of plants capable of rehabilitating such soils (Hoseinpour *et al.*, 2020; Opoku *et al.*, 2020; Lu *et al.*, 2021).

3.2 Main Contributions and Proposals on Phytoremediation in Mining

As a result of reviewing the articles, between two and three proposals and/or contributions per article were identified in relation to phytoremediation in mining. These proposals and/or contributions, which total 88, were categorized and classified according to their frequency of occurrence (see Figure 2).

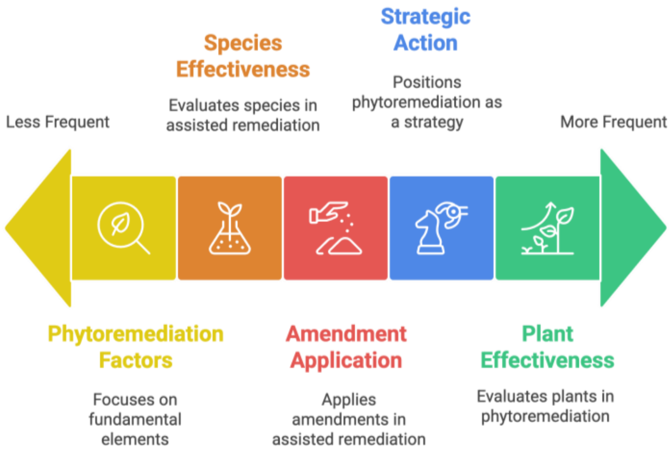

Figure 2. Frequency of Proposals and/or Contributions Made in the Articles.

Among the proposals and/or contributions with the highest frequency is “Effectiveness of Plants in Phytoremediation,” with a frequency of 30. This proposal and/or contribution refers to the selection and application of plants as an ecological and sustainable means for the remediation of soils contaminated by heavy metals. Another proposal and/or contribution with high frequency is “Phytoremediation as a Strategic Action,” which has a frequency of 29. This proposal and/or contribution describes phytoremediation as an ecological, economic, and sustainable solution for the reduction and/or elimination of heavy metals in contaminated soils, thereby ensuring environmental sustainability. This coincides with what (Chen *et al.*, 2019; Lebrun *et al.*, 2021; Pusz, Wiśniewska and Rogalski, 2021) noted, who state that phytoremediation is an ecological and economic method that allows for the reduction of risks present in contaminated soils and, at the same time, ensures their rehabilitation.

4. Discussion

The reviewed literature shows that phytoremediation has become established as an economic, sustainable, and ecological alternative for the recovery of soils contaminated with heavy metals. However, the analyzed studies differ in the depth of their theoretical approaches and in the practical validation of the applied methods. While some authors highlight its economic and environmental feasibility (Cai et al., 2021; Reboredo et al., 2021; Otunola et al., 2023), others note that its effectiveness depends on the correct identification of contaminants, species adaptability, and remediation time. This diversity reveals that the proper execution of the process still faces methodological challenges that limit its predictability.

Conceptually, two main approaches prevail, the first aims to demonstrate the capacity of plants to remove heavy metals (Chen et al., 2019; Li et al., 2020; Opoku et al., 2020; Pusz et al., 2021), and the second focuses on developing strategies to optimize this capacity through planned actions (Vela-García et al., 2019; Cruzado-Tafur et al., 2021; Singh et al., 2022). Both approaches are complementary, yet the literature shows that most studies remain at a theoretical-experimental level, with limited field validation. This suggests a gap between experimental knowledge and its practical application in real mining contexts.

Regarding the selection of species and amendments, there is general agreement on prioritizing plant adaptability as a key success factor (Singh et al., 2022); however, other authors argue that the integration of microorganisms can enhance efficiency and shorten treatment times (Madline et al., 2021; Nurfitriani et al., 2023; Saldarriaga et al., 2023). This comparison suggests a shift from traditional plant-based approaches toward microbial alternatives that broaden the biotechnological spectrum of phytoremediation.

Likewise, recent literature has explored the use of organic residues and compost as alternative inputs. Garau et al. (2021) and Baragaño et al. (2021) highlight their contribution as nutrient sources and their potential to improve soil structure, while Cárdenas-Aguiar et al. (2020) emphasize their role in enhancing the sustainability of the process. However, Bortnikova et al. (2022) warn that the limited number of trials makes it difficult to generalize results, reinforcing the need for more comparative studies. This tension between innovation and empirical evidence defines the current state of knowledge.

Overall, the reviewed studies show convergence toward the search for low-cost and highly sustainable solutions, although they diverge in terms of empirical validation and scale of application. The evidence indicates that, beyond methodological diversity, phytoremediation remains a promising alternative whose consolidation depends on integrating theoretical progress with a critical evaluation of experimental results.

5. Conclusions

Firstly, the phytoremediation can be considered an effective and sustainable alternative for mitigating heavy metal contamination in soils in mining areas. Throughout the 60 analyzed studies, it is evident that plants (especially those with hyperaccumulating characteristics), plant growth-promoting bacteria (PGPB), and various organic amendments (such as compost and biochars) constitute the main elements employed to optimize the decontamination process. This evidence directly addresses the research question, as it highlights the most used inputs in phytoremediation and corroborates their relevance in the removal of heavy metals.

Secondly, it is observed that the effectiveness of these strategies largely depends on the adaptability of the selected plant species, the suitability of the applied bacteria, and the accurate characterization of the contaminants present in the soil. While most studies agree on the importance of appropriately selecting plants and bacteria, as well as incorporating amendments that enhance their action, empirical gaps still exist related to the optimization of dosages, application timings, and specific edaphoclimatic conditions of each mining zone. Phytoremediation offers a promising approach to mining soil remediation, as it is more economical and environmentally friendly than conventional methods. However, further field-scale research is recommended, as well as the integration of new monitoring and evaluation technologies, in order to refine application protocols and ensure successful soil rehabilitation.

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