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EDITORIAL

Ecological rehabilitation of mine tailings

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A mine-tailing site undergoing ecological rehabilitation. Pioneer plants are growing in the tailing-impoundment area.

Tailings are residue minerals left behind from mining and processing ores and their sustainable rehabilitation is one of the most costly and difficult challenges facing the global mining industry. Tailings are finely ground particles that are conducive to physical compaction and exhibit extreme geochemical properties (e.g., highly alkaline/acidic, saline), and generate dust pollution risks when dry. Tailings from mining precious and base metals often contain high levels of toxic metals and metalloids in gangue minerals and residual economic minerals, presenting long-lasting risks of air/soil/water contamination. These characteristics of mine tailings are inhibitory to the colonisation of plants for ecosystem development. The abundant minerals in tailings without soil-like structure and properties make conventional soil reclamation measures ineffective.

Ecological engineering of tailings has been advocated to change tailings' mineralogy, improve physicochemical properties, and accelerate soil formation (i.e. pedogenic processes), allowing the re-colonisation of microbial communities and pioneer plant species (Huang et al. 2012). These early settlers, in turn, act as powerful biological drivers to advance soil formation, develop functional soil system, reduce soil metal(loid)s contamination, and stimulate the evolution of sustainable plant communities. After the initial proposition of the conceptual model and technological framework of "Ecological Engineering of Tailings" (Huang et al. 2012, 2014), an increasing volume of research in the field of mine tailing rehabilitation has improved our confidence that ecological engineering of tailings into Technosol (soil-like growth substrate) is a promising technology that would lead to sustainable rehabilitation of tailings (Wu et al. 2019, 2021, 2023). So, this Special Issue is timely that encourages further research in this important area.

Before demonstrating the themes and content of this Special issue, it is necessary to clarify several terms, including "remediation", "reclamation", "rehabilitation", and "restoration". "Remediation" usually means the processes to lower the mobility and biotoxicity of pollutants in contaminated soil via various technologies, such as leaching and/or immobilisation. "Reclamation" means the processes to reclaim the original soil use value by improving the quality and functions of degraded or contaminated soil to be compatible with economic land use (e.g., cropping). Both soil "remediation" and "reclamation" focus on the improvement of soil properties and functions which have already been developed but degraded or destroyed. These two terms are not suitable for mine tailings which have not yet been developed into soil-like medium. "Rehabilitation" refers to the engineering of pedogenic processes starting from parent materials towards the development of key soil physical and biogeochemical properties and functions. This is particularly relevant to mine wastes, such as tailings, as they are mixtures of minerals without soil-like structure and functions. "Rehabilitation" is widely used in literature about developing mine sites into non-polluting and sustainable ecosystems in Australia and UK. Compared with "rehabilitation", soil "restoration" is the ultimate goal of "rehabilitation" to reach the initial soil properties and eco-functionalities before disturbances. "Restoration" is usually used in managing degraded lands and forest soils, and not suitable and feasible for managing mine wastes such as tailings. The key mineralogical basis and pedogenic state of mine tailings justify the use of "rehabilitation" in this Special Issue, which also aims to set the reference for future publications in this research topic area.

The main themes of this Special Issue "Ecological Rehabilitation of Mine Tailings" include: (1) the adaptation of microbes and plants to the adverse environments in tailings or tailings-contaminated soils; (2) the roles of plants and microbes in modifying tailing/soil properties—physicochemical improvement, physical structure development, organic matter (OM) stabilisation and metal(loid) mobilisation/stabilisation for sustainable rehabilitation of tailings or tailing-contaminated soils; and (3) agricultural management, phyto-management, and advanced materials for improvement of plant-microbial performance and functioning in tailings or tailings-contaminated soils. The call for papers was widely received by the scientific community, especially researchers in the field of mine site rehabilitation research, leading to 15 research papers published in this Special Issue.

Three of the research articles focused on the adaptation of plants and microbes to the adverse environments in the tailings or tailings-affected mining areas. Fleurial et al. (2024) reported that in the liquid tailings originating from oil-sand processing, waterlogging-tolerant tree species could not grow well due to high levels of salt in tailings' pore water. Particularly, environmental conditions like root hypoxia further aggravated the negative effects of the aqueous phase of tailings on plant performance. However, after early ecological engineering of mine tailings, Li et al. (2024a) found the legume *Acacia auriculiformis* could grow better in iron ore tailings eco-engineered with exogenous OM and pioneer plant colonisation. Furthermore, this legume formed nodules and promoted N_2 fixation in eco-engineered iron ore tailings. Compared with plants, microbial communities are more tolerant and adaptive in the initial conditions of tailings subject to organic and inorganic amendments. For instance, Chen et al. (2024) found that there were significant differences in bacterial community structure and predicted functions in tailing ponds subject to different methods of inputs and amendments. Aggregate spray seeding particularly favoured Bacillaceae and Rhizobiaceae development for nitrogen cycling and ecological rehabilitation of tailings pond.

After establishing in the tailings, microbes and plants play important roles in advancing soil property development and metal(loid) mitigation in mine tailings. Four articles highlight the role of microbes and plants in soil development. Two of them focus on the microbial OM formation and stabilisation in bauxite residues, as key processes for soil development. Guo et al. (2024) revealed the soil OM formation through humification in bauxite residues amended with exogenous OM as driven by microbial activities and carbon cycle-related enzymes. Furthermore, Xue et al. (2024) elucidated the important functions of Ca ions in OM stabilisation by alkaline minerals in bauxite residues. Tolerant pioneer plant colonisation further stimulates physicochemical property improvement for the development of soil-like conditions in mine tailings. Zhang et al. (2024) showed that a salinity-tolerant plant species, *Elymus dahuricus* (Gramineae), with a fibrous root system can develop in bauxite residues and further decrease the alkalinity, and improve nutrient levels, enzyme activities and aggregate stability in bauxite residues. In a meta-analysis carried out by Li et al. (2024b), the positive roles of vegetation growth in soil development were evidenced by the increased soil organic carbon stock and water-holding capacity and physical context in post-mining land.

Five articles target the key role of microbes and plants in metal(loid) mobilisation or stabilisation in tailings. Dillon and Courtney (2024) assessed non-essential metal(loid) availability and concentrations in vegetation in a bauxite residue storage area and found a low risk of metal(loid) contamination and food chain transfer. However, in the tailings with high concentrations of metal(loid) contaminants, plants developed toxicity symptoms. In this case, some tolerant microbes were found to improve plant performance and regulate metal(loid) behaviour in plant-soil system for various purposes of remediation. Alami et al. (2024) isolated an indigenous microsymbiont *Ensifer meliloti* sv. *rigiduloides* and found that it significantly enhanced the growth and performance of *Robinia pseudoacacia* plants in soil under lead-stress. Wu et al. (2024) reported that the plant growth promoting bacteria (PGPB) *Serratia marcescens* SNB6 improved rhizosphere bacterial diversity and reduced cadmium phytotoxicity in the hyperaccumulator plant *Chrysopogon zizanioides* through regulating key gene expression. In phosphate-mining affected soils, Li et al. (2024c) investigated numerous microbial communities particularly endophytic bacteria in roots/rhizosphere of vegetables and crops grown in phosphate-mining areas. Some bacterial strains were isolated and tested to be resistant to metal(loid) stress, showing potential in further ecological rehabilitation of phosphate-mining-affected land. Furthermore, some functional microbes can directly regulate metal(loid) speciation and mobility in soil. For instance, Horváthová et al. (2024) found that soil bacterial strains of *Cupriavidus oxalaticus* and *Cupriavidus metallidurans* efficiently stimulated the leaching of metal(loid)s such as arsenic and antimony in soil, with potential use in remediating contaminated soils or eco-engineering mine tailings.

Three articles emphasise the agricultural management, phyto-management, and advanced materials used for the improvement of plant growth and functions in tailings or tailings-contaminated soils for efficient rehabilitation of mine sites. Borbón-Palomares et al. (2024) demonstrated the effects of compost and nutrients and/or the soil capping approach (using combinations of soil, gravel, clay, and tailings layers) on plant survival and metal(loid) accumulation in abandoned mine tailings. They revealed that a soil capping method was most efficient in improving plant performance and metal(loid) stabilisation. Creamer et al. (2024) indicated that the additions of dolomite minerals, together with compost, and endophyte seed facilitated the growth of *Bouteloua curtipendula* seedlings in polymetallic tailings, but might cause the solubilisation of metal(loid)s. Díaz et al. (2024) further revealed that the combination of functional materials such as nano zero valent iron (nZVI) and dunite mining waste, as well as compost amendment simultaneously immobilised metal(loid)s and improved growth of *Sinapis alba* plants in a metal(loid)-polluted soil.

Overall, the articles in this Special Issue deliver up-to-date findings in the research field of ecological rehabilitation of mine tailings, from three aspects: (a) plant and microbial colonisation and adaptation to tailings environment, (b) plant/microbial functions in tailing property development and metal(loid) stabilisation, and (c) agricultural management and functional materials in tailings' amendments and improvements for tailings' ecological rehabilitation. These findings provide important information on plant and microbial driven biogeochemical processes in mine tailings, as foundation processes of sustainable rehabilitation of mined land. These findings will also bring the urgency and R&D (Research and Development) requirements to the global mining industry's attention to help achieve sustainable rehabilitation of mine tailings.

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Order of publication

Publication order	Manuscript number	
1	PLSO-D-22-01827	Root hypoxia aggravates the effects of saline tailings water on the growth and physiology of woody plants
2	PLSO-D-23-01395	Natural nodulation and nitrogen fixation of Acacia Auriculiformis grown in technosol eco-engineered from Fe ore tailings
3	PLSO-D-23-01209	Effects of different ecological restoration methods on the soil bacterial community structure of a light rare earth tailings pond
4	PLSO-D-22-01623	Organic amendments enhanced the humification degree in soil formation of bauxite residue
5	PLSO-D-22-02068	Effect of calcium ions on the interaction of alkaline minerals with dissolved organic matter: Implications for organic carbon sequestration in bauxite residue
6	PLSO-D-22-01659	Tolerant plant growth improves the conversion of bauxite residue to soil-like substrates by altering aggregate stability
7	PLSO-D-22-02090	Positive effects of vegetation restoration on the soil properties of post-mining land
8	PLSO-D-23-01059	Availability and Transfer of Non-Essential Elements in a Rehabilitated Bauxite Residue Grassland System
9	PLSO-D-23-00085	The inoculation with Ensifer meliloti sv. rigiduloides improves considerably the growth of Robinia pseudoacacia under lead-stress
10	PLSO-D-22-01516	The effect of plant growth-promoting bacteria application on rhizospheric microbial community and cadmium related regulatory network of Chrysopogon zizanioides¬†in mining soil
11	PLSO-D-22-01495	Phosphorus mining activities alter endophytic bacterial communities and metabolic functions of surrounding vegetables and crops
12	PLSO-D-23-01049	Aerobic release of arsenic and antimony from mine soils by biostimulation of indigenous microbial activity and bioaugmentation with Cupriavidus genera of bacteria
13	PLSO-D-22-02013	Phytostabilization alternatives for an abandoned mine tailing deposit in northwestern Mexico.
14	PLSO-D-23-00704	A combined compost, dolomite, and endophyte addition is more effective than single amendments for improving phytorestoration of metal contaminated mine tailings
15	PLSO-D-22-01735	Nanoscale zero-valent iron mitigates arsenic mobilization and accumulation in Sinapis alba grown on a metal(loid)-polluted soil treated with a dunite mining waste-compost amendment

Data Availability There is no data in this manuscript.

Declarations

Competing interests We declare that the authors have no competing financial interests.

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