Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Remediation of Heavy Metal-Contaminated Soils in Alpine and Arid Mining Regions: Synthesis and Performance of a Multifunctional Amendment

Jie Zhou
Chengdu University of Technology
Peicong Zhang
zhangpeicong@cdut.cn

Chengdu University of Technology
Jinhua Luo
Chengdu University of Technology
Yi Huang
Panzhihua Pangang Group Ming Company
Jialin He
Chengdu University of Technology
Jinshu Zhang
Tibet University
Yubin Li
Tibet University
Chengye Yang
Tibet University

Research Article

Keywords: Qinghai-Tibet Plateau, Freeze-thaw cycles, Heavy metal immobilization, multifunctional amendment, mine soil remediation

Posted Date: June 1st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9691982/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Water, Air, & Soil Pollution on October 12th, 2026. See the published version at https://doi.org/10.1007/s11270-026-10039-9.

Remediation of Heavy Metal-Contaminated Soils in Alpine and Arid Mining Regions: Synthesis and Performance of a Multifunctional Amendment

Jie Zhou[1], Peicong Zhang[1.2*] , Jinhua Luo[3], Yi Huang [4,2],Jialin He[3] ,Jinshu Zhang[5], Yubin Li[5] ,Chengye Yang[5],

1 College of Materials and Chemistry and Chemical Engineering, Chengdu University of Technology, Chengdu 610059, Sichuan, P.R. China

2 State Key Laboratory of Geo-Hazard Prevention and Earth Environment Protection, Chengdu 610059, Sichuan, P.R. China

3 College of Ecology and Environment, Chengdu University of Technology, Chengdu 610059, Sichuan, P.R. China

4 Panzhihua Pangang Group Ming Company, Panzhihua, 61700, Sichuan, P.R. China

5 School of Engineering, Tibet University, Lhasa850000, P.R. China

* Corresponding author. E-mail addresses: zhangpeicong@cdut.cn

First author. E-mail addresses: 2200766132a@gmail.com

Abstract

Heavy metal (HM) contamination, freeze-thaw (F-T) cycles, and dry, nutrient-poor conditions make the soils in the lead-zinc mining areas of the Qinghai-Tibet Plateau even worse, making it harder for plants to grow. To solve these problems, an inorganic-organic composite multifunctional amendment was made using solid waste from the area. The best mass ratio of diatomite, biochar, gypsum, magnesium hydroxide, and soil was found to be 5:6:1:1.45:103. Using this composite amendment improved the soil's physical and chemical properties a lot. The saturated water capacity and water-holding capacity went up by 14.71% and 23.33%, respectively. Also, the cation exchange capacity (CEC), phosphorus retention, and potassium retention capacities all went up by 44.88%, 20.34%, and 100.70%, respectively. Under F-T conditions, the modified soil showed a two- to three-fold improvement in both adsorption capacity and efficiency for different HMs in single and multi-metal systems when compared to the control (CK). The removal efficiency for Pb^{2+} was especially high, at over 80%. Thermodynamic and kinetic analyses elucidated that the adsorption of Pb^{2+} and Zn^{2+} conformed to the Freundlich isotherm, suggesting multilayer adsorption on heterogeneous surfaces as the principal mechanism. Chemisorption processes, like surface complexation and precipitation (which fit the pseudo-second-order kinetic model), were mostly responsible for the immobilization of Pb^{2+}. On the other hand, physical diffusion (which fits the pseudo-first-order model) was mostly responsible for the adsorption of smaller radius ions (Zn^{2+}, Cu^{2+}, Cd^{2+}). Finally, greenhouse pot trials with ryegrass (Lolium perenne L.) confirmed that the amendment not only significantly reduced the bioavailability of heavy metals during F-T cycles but also improved water and nutrient retention, resulting in significant increases in plant height and biomass.

Keywords: Qinghai-Tibet Plateau; Freeze-thaw cycles; Heavy metal immobilization; multifunctional amendment; mine soil remediation

1. Introduction

The Qinghai-Tibet Plateau (QTP) is known around the world as the "Third Pole" and the "Asian Water Tower." It is an important ecological barrier that controls the climate around the world and makes sure that Asia has enough water. The area has a lot of mineral resources, especially in mines like Yulong, Jiama, and Mengya'a. The lead-zinc (Pb-Zn) reserves are 40 million tonnes, which is

more than 30% of China's total reserves (Yang et al., Yang, Y., Shi, L., Zhang, T., Guo, X., Wang, Y., & Chen, G. (2019). Research on geological environment problems and prevention measures of mineral resources development in plateau alpine canyon areas: A case study of Jiama and Yulong copper mines in Tibet. *Acta Geologica Sichuan*, *39*(6), 394–398. https://doi.org/10.3969/j.issn.1006-0995.2019.S1.019 ; Song et al., Song, M., Zhong, K., & Bao, X. (2019). Study on ore fabric of the Mengya lead-zinc de-posit in Jiali County, Tibet. *West-China Exploration Engineering*, *31*(12), 108–111. https://doi.org/10.3969/j.issn.1004-5716.2019.12.051). However, the large-scale extraction of these resources has led to serious environmental problems, even though it has helped the economy grow (Zhang et al., Zhang, J., Li, C., Jia, Z., Liu, X., & Meng, M. (2022). Application of functional microorganisms in ecological restoration of abandoned mines. *Journal of Nanjing Forestry University (Natural Sciences Edition)*, *46*(6), 146–156. https://doi.org/10.12302/j.issn.1000-2006.202206012 ; Punia, Punia, B. (2021). Role of temperature, wind, and precipitation in heavy metal contaminatio-n at copper mines: A review. *Environmental Science and Pollution Research*, *28*(4), 4056–4072. https://doi.org/10.1007/s11356-020-11580-8 ; Yin et al., Yin, Y., Wang, X., Hu, Y., Li, F., & Cheng, H. (2023). Soil bacterial community structure in the habitats with different levels of heavy metal pollution at an abandoned polymetallic mine. *Journal of Hazardous Materials*, *442*, Article 130063. https://doi.org/10.1016/j.jhazmat.2022.130063). Recent surveys show that soils near major Pb-Zn mining areas on the QTP, like Xitieshan in Qinghai and Zhaxikang in Tibet, are very polluted. Pb^{2+} and Zn^{2+} concentrations have been measured at levels as high as 2,540 mg/kg and 5,000 mg/kg, respectively, which is many times higher than the limits set by the government. This is often accompanied by high levels of copper (Cu) and cadmium (Cd) co-contamination (Huang et al., Huang, C., Huang, M., Hu, G., & Zeng, H. (2020). Influence and attribution of the casca-de hydropower station operation on the hydrological regimes in Lhasa River. *Journal of Water Resources and Water Engineering*, *31*(5), 62–69. https://doi.org/10.11705/j.issn.1672-643X.2020.05.10 ; Hu et al., Hu, Z., Wang, C., Li, K., & Zhu, X. (2018). Distribution characteristics and pollution assessment of soil heavy metals over a typical nonferrous metal mine area in Chifeng, Inner Mongolia, China. *Environmental Earth Sciences*, *77*(18), Article 638. https://doi.org/10.1007/s12665-018-7771-1). This coexistence of multiple metals makes a very complicated pollution matrix. The different physicochemical properties of these elements make traditional methods of cleaning them up ineffective, which makes it even harder to restore the environment. Moreover, the persistent dispersion of these heavy metals causes significant phytotoxicity, hindering root colonization (Feng et al., Feng, W., Yang, F., Cen, R., Liu, J., Qu, Z., Miao, Q., & Chen, H. (2021). Effects of st-raw biochar application on soil temperature, available nitrogen and growth of cor-n. *Journal of Environmental Manage-*

ment, *277*, Article 111331. https://doi.org/10.1016/j.jenvman.2020.111331). Plants in the QTP suffer from serious water and nutrient shortages because of the harsh, extreme climate, which is characterized by long periods of dryness, freezing temperatures, and frequent freeze-thaw (F-T) cycles. This speeds up ecological degradation (Wang, Wang, L., Wu, Q., & Jiang, G. (2020). The effect of desertification on frozen soil on the Qinghai-Tibet plateau. *Science of the Total Environment*, *711*, Article 134640. https://doi.org/10.1016/j.scitotenv.2019.134640).

At this time, the most common ways to clean up soil are soil washing, electrokinetic remediation, phytoremediation, in-situ immobilization and so on (Lin et al., Lin, H., Wang, Z., Liu, C., & Dong, Y. (2022). Technologies for removing heavy metal f-rom contaminated soils on farmland: A review. *Chemosphere*, *305*, Article 135457. https://doi.org/10.1016/j.chemosphere.2022.135457). Among these, in situ immobilization through soil amendments has become a very practical method. It is popular because it is cheap (only 10%–20% of the cost of replacing or washing soil), works quickly (reducing HM leaching toxicity within hours), and is easy to use (no need for heavy machinery) (Bai et al., Bai, X., Zhang, E., Wu, J., Ma, D., Zhang, B., Zhang, C., Tian, F., Zhao, H., & Wang, B. (2024). Effects of different modified materials on soil fungal community structure in saline-alkali soil. *Environmental Science*, *45*(6), 3562–3570. https://doi.org/10.13227/j.hjkx.202306086 ; Huang et al., Huang, P., Fang, Z., Yu, H., Zhang, F., & Huang, J. (2023). Effects of combined application of different amendments on physicochemical properties of alkalized soil and growth of Lycium barbarum in Hetao Irrigation District. *Agricultural Research in the Arid Areas*, *41*(5), 12–19. https://doi.org/10.7606/j.issn.1000-7601.2023.05.13). Nonetheless, conventional amendments demonstrate significant constraints when utilized in the alpine mining areas of the QTP. Research indicates that traditional materials, including lime, phosphates, and unaltered biochar, exhibit insufficient saturation adsorption capacities; for example, specific agricultural biochars display a Pb^{2+} adsorption capacity of under 2 mg/g, along with suboptimal environmental stability (Anastopoulos et al., Anastopoulos, I., Ahmed, M. J., Ojukwu, V. E., Danish, M., Stylianou, M., & Ighalo, J. O. (2024). A comprehensive review on adsorption of Reactive Red 120 dye using various adsorbents. *Journal of Molecular Liquids*, *394*, Article 123719. https://doi.org/10.1016/j.molliq.2023.123719). Lime can temporarily stop heavy metals from moving by raising the pH of the soil, but it is very likely to turn to carbon dioxide when it is exposed to the weather for a long time. This causes the pH to slowly rise again, which then causes the HMs to move again (Park et al., Park, B. J., Nam, S. H., Jeong, S. S., Yoon, J.-H., Kirkham, M. B., Yang, J. E., & Kim, H. S. (2026). Valorization of phosphogypsum into carbon-neutral lime for soil lead i-mmobilization. *Environmental Technology & Innovation*, *42*, Article 104879. https://doi.org/10.1016/j.eti.2026.104879). Moreover, current research primarily concentrates on single-metal systems, exhibiting a significant deficiency of studies that explore multi-metal co-contamination. In QTP mining areas, Pb, Zn, Cu, and Cd frequently exhibit strong positive correlations in co-contamination, resulting in vigorous competitive sorption dynamics. Conventional amendments generally demonstrate a strong affinity for particular ions (e.g., Pb^{2+}), resulting in the immobilization of others (e.g., Cd^{2+}, Zn^{2+}) (Montagnoli et al., Montagnoli, A., Baronti, S., Alberto, D., Chiatante, D.,

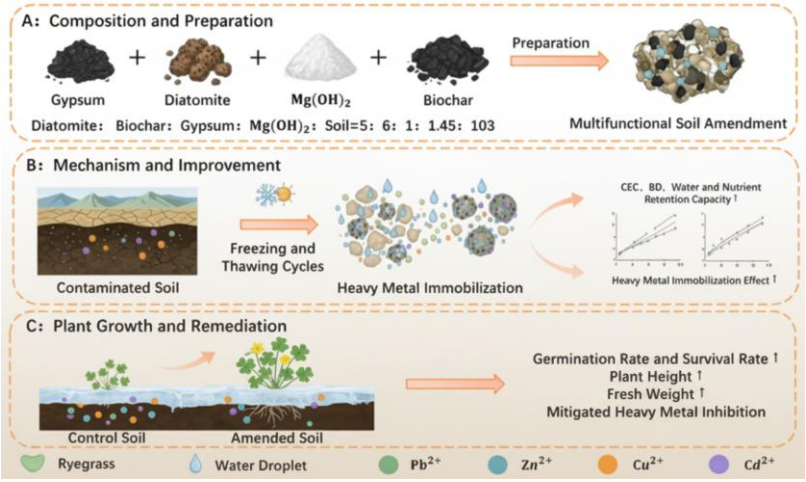
Scippa, G. S., & Terzaghi, M. (2021). Pioneer and fibrous root seasonal dynamics o f Vitis vinifera L. are affected by biochar application to a low fertility soil: A rhizob ox approach. *Science of the Total Environment*, *751*, Article 141455. https://doi.org/10. 1016/j.scitotenv.2020.141455 ; Xia et al., Xia, H., Kong, W., Liu, L., Lin, K., & Li, H. (2021). Effects of harvest time and desali-nation of feedstock on Spartina alterniflo ra biochar and its efficiency for Cd2+ remo-val from aqueous solution. *Ecotoxicology and Environmental Safety*, *207*, Article 111309. https://doi.org/10.1016/j.ecoenv.2020.111 309 ; Li et al., Li, L., Lei, Y., Chen, Q., Deng, X., Bao, H., Zhaqiong, B., & Sun, G. (2023). Changes of soil total carbon and plant root characteristics during the restor ation of alpine desertification grassland in Zoige. *Chinese Journal of Ecology*, *42*(2), 282–290. https://doi.org/10.13292/j.1000-4890.202302.011). Under the extreme arid and F-T conditions that are common in the QTP, big changes in the structure of soil pore s break up the stable complexes and precipitates that form between amendments and HMs. This presents a significant obstacle to the enduring stability of the remediation, making single-component amendments inadequate for guaranteeing prolonged soil reco very within the region's stringent ecological boundaries (Holanda et al.,

Holanda, S. F., Vargas, L. K., & Granada, C. E. (2025). Challenges for sustainable produ-ction in sandy soils: A review. *Environment, Development and Sustainability*, *27*(1), 53–66. https://doi.org/10.1007/s10668-023-03894-3).

To address these significant deficiencies, this study developed an innovative organic-inorganic multifunctional composite amendment by co-formulating magnesium hydroxide (Liu et al., Liu, X., Liao, C., Lin, L., Gao, H., Zhou, J., Feng, Z., & Lin, Z. (2020). Research progress in the environmental application of magnesium hydroxide nanomaterials. *Surfaces and Interfaces*, *21*, Article 100701. https://doi.org/10.1016/j.surfin.2020.100701) with locally sourced Tibetan gypsum (Jia et al., Jia, W., Li, J., Shen, C., Li, G., Li, H., Fan, G., Zhou, G., & Cao, Y. (2025). Research advances in phosphogypsum flotation purification: Current status and prospects. *Separation and Purification Technology*, *354*, Article 129244. https://doi.org/10.1016/j.seppur.2024.129244), diatomite (Ding et al., Ding, R., Jin, X., & Liu, G. (2021). Characteristics of diatomite mineral resources in Chi-na and analysis of supply and demand situation. *Jilin Geology*, *40*(4), 25–29. https://doi.org/10.3969/j.issn.1001-2427.2021.04.005 ; Li et al., Li, Z., Wang, G., Li, Z., Wang, H., Guo, X., Zhao, Q., & Nan, Y. (2021). Current situation and development countermeasures of diatomite utilization in China. *China Non-Metallic Minerals Industry*, *23*(3), 1–5. https://doi.org/10.3969/j.issn.1007-9386.2021.03.001), and biochar derived from agricultural waste (Lopez et al., López, J. E., Arroyave, C., Aristizábal, A., Almeida, B., Builes, S., & Chavez, E. (2022). Reducing cadmium bioaccumulation in Theobroma cacao using biochar: Basis for scaling-up to field. *Heliyon*, *8*(6), Article e09790. https://doi.org/10.1016/j.heliyon.2022.e09790). The components of this amendment have a strong synergistic effect on each other. For example, biochar, which has a lot of microporosity and reactive functional groups, greatly increases the amount of

Fig 1 Schematic illustration of the research framework

organic carbon in barren soils (Li et al., Li, Z., Chen, K., Zhai, S., Yang, L., Yu, T., Yuan, H., Zeng, B., Yang, L., Qi, F., & Zhu,H. (2024). Preparation of biochar from anaerobic digested sludge for enhancement of sludge dewatering. *Chemosphere*, *362*, Article 142687. https://doi.org/10.1016/j.chemosp- here.2024.142687). In addition to holding more water, its dark matrix absorbs sunlight to raise soil temperature in cold areas (the albedo effect) and effectively traps Pb^{2+} and Cd^{2+} through physical adsorption and surface complexation (Bi et al., Bi, H., Xu, J., Li, K., Li, K., Cao, H., & Zhao, C. (2024). Effects of biochar-coated nitrogen fertilizer on the yield and quality of bok choy and on soil nutrients. *Sustainability*, *16*(4), Article 1659. https://doi.org/10.3390/su16041659). Gypsum, a mineral that is very common in Tibet, gives the body important Ca and S nutrients (Qi et al., Qi, J., Zhu, H., Zhou, P., Wang, X., Wang, Z., Yang, S., Yang, D., & Li, B. (2023). Application of phosphogypsum in soilization: A review. *International Journal of Environmental Science and Technology*, *20*(9), 10449–10464. https://doi.org/10.1007/s13762-023-04783-2). The released Ca^{2+} replaces exchangeable acidity and makes soil aggregation better. In particular, its sulfate ions cause Pb^{2+} to become stuck by making very stable $PbSO_4$ precipitates (Hu et al., Hu, C. (2023). Effect of phosphogypsum on adsorption and desorption characteristics of m-agnesium in loess soil. *Science Technology and Engineering*, *23*(30), 12842–12849. https://doi.org/10.3969/j.issn.1671-1815.2023.30.009). Diatomite has an ultra-high specific surface area and natural hierarchical porosity, which makes it great at adsorbing Pb^{2+}, Zn^{2+}, and Cd^{2+} (Zhu et al., Zhu, J., Liu, J., Fang, Y., Wu, Z., & Zhang, Y. (2025). Adsorption performance and mechanism of Cd in aqueous solution by modified diatomite. *New Chemical Materials*, *53*(3), 203–209. https://doi.org/10.19817/j.cnki.issn1006-3536.2025.03.031 ; Gao et al., Gao, R., Chen, H., Li, C., Liang, X., Hou, X., & Yang, B. (2024). Preparation of diatomite-based porous ceramics and their adsorption properties for Cu^{2+}. *Ceramics International*, *50*(23), 50153–50162. https://doi.org/10.1016/j.ceramint.2024.09.362). $Mg(OH)_2$ is a pH buffer that slowly releases and is safe for the environment. It helps Zn^{2+}, Cu^{2+}, and Cd^{2+} form insoluble hydroxide precipitates in mildly alkaline conditions without causing the severe soil compaction or drastic physicochemical changes that are common with regular lime (Li et al., Li, H., Gao, Y., Zheng, Y., Li, N., Zhang, L., & Liu, Z. (2023). Adsorption performance of cross-linked starch loaded magnesium hydroxide composite for Cu^{2+}. *Industrial Water Treatment*, *43*(11), 161–166. https://doi.org/10.19965/j.cnki.iwt.2022-1165). This study seeks to simultaneously improve soil water and nutrient retention, enhance physicochemical properties, and achieve effective heavy metal immobilization in cold-arid Pb-Zn mining areas by leveraging the unique benefits of these four components, while also promoting solid waste valorization. Ultimately, this work provides a robust theoretical and practical paradigm for large-scale ecological engineering in alpine mine remediation. The conceptual framework of this study is illustrated in Fig 1.



2. Experiments and methods

2.1 Experimental materials and reagents

Gypsum and diatomite utilized in this study were sourced from local mine tailings in Tibet. Biochar was produced via the pyrolysis of locally collected wheat straw at 600°C. Magnesium hydroxide was purchased from Chengdu Kelong Chemical Reagent Factory. All aforementioned materials were ground and passed through a 60-mesh sieve. Other chemical reagents used were of analytical grade (AR). Sodium hydroxide, hydrochloric acid, potassium dihydrogen phosphate, and cadmium acetate dihydrate were procured from Chengdu Kelong Chemical Reagent Factory. Lead nitrate trihydrate, zinc nitrate hexahydrate, and copper nitrate hexahydrate were supplied by Sinopharm Chemical Reagent Co., Ltd. All other reagents and solvents were commercially available and used as received without further purification.

2.2 Experimental Methods

2.2.1 Preparation and Optimization of the Composite Soil Amendment

An orthogonal experimental design was employed to optimize the mass ratios of diatomite, biochar, gypsum, and magnesium hydroxide. Soil samples collected from the alpine-arid regions of Tibet were initially air-dried, pulverized, and passed through a standard sieve. The sieved soil was then homogeneously incorporated with varying proportions of the composite amendments and transferred into experimental pots. All treatments underwent a 30-day incubation period with regular irrigation to maintain soil moisture and facilitate physicochemical interactions. Upon completion of the incubation, soil physicochemical properties and the adsorption efficacy for Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+} (in both single and multi-metal systems) were systematically evaluated. The influence of

each component on soil pH and heavy metal immobilization was rigorously investigated. Based on a comprehensive assessment of these parameters, the optimal formulation was identified and designated as EK.

2.2.2 Adsorption experiment

To evaluate the adsorption performance of the optimized amendment (EK), batch experiments were conducted under freeze-thaw (F-T) conditions. For all experiments, an exact dose of 1.0 g of EK was introduced into 50 mL of metal solution and equilibrated for 24 h.

Single and Multi-metal Adsorption: The adsorption efficacy of EK for Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+} in both single- and multi-metal systems was compared. The initial concentrations for the single-metal systems (Pb^{2+}: 100.13 mg/L, Zn^{2+}: 101.11 mg/L, Cu^{2+}: 99.69 mg/L, and Cd^{2+}: 101.19 mg/L). Respectively, the initial concentrations for the multi-metal system were (Pb^{2+}: 100.56 mg/L, Zn^{2+}: 100.27 mg/L, Cu^{2+}: 98.18 mg/L, and Cd^{2+}: 102.56 mg/L).

Experiment on pH value: The influence of initial pH values (ranging from 3 to 7) on the adsorption performance of EK toward a Pb^{2+}-Zn^{2+}-Cu^{2+}-Cd^{2+} multi-metal system (Pb^{2+}: 100.27 mg/L, Zn^{2+}: 101.76 mg/L, Cu^{2+}: 10.18 mg/L, and Cd^{2+}: 5.91 mg/L) was comparatively investigated.

Experiment on initial concentration: The effect of initial concentrations on adsorption was investigated by varying the initial concentrations of Pb^{2+} and Zn^{2+} while maintaining constant initial concentrations of Cu^{2+} (10.18 mg/L) and Cd^{2+} (5.91 mg/L). The Pb^{2+}/Zn^{2+} concentration gradients were set at 1.16/0.99 mg/L, 5.16/5.67 mg/L, 21.51/20.21 mg/L, 50.31/49.84 mg/L, 90.63/86.54 mg/L, 166.03/152.61 mg/L, and 621.15/597.19 mg/L in the multi-metal system.

Experiment on time of adsorption: To evaluate adsorption kinetics, the influence of contact time (0–1440 min) on the multi-metal system (Pb^{2+}: 100.27 mg/L, Zn^{2+}: 101.76 mg/L, Cu^{2+}: 10.18 mg/L, and Cd^{2+}: 5.91 mg/L) was comparatively examined.

The evaluation of adsorbent performance was accomplished by measuring the unit adsorption capacity (Qe) and the adsorption rate (R), which were calculated using equations (1) and (2).

$$R=\frac{C_0-C_e}{C_e}\times 100\% \quad (1)$$

$$Q_e=\frac{C_0-C_e}{m}V \quad (2)$$

Where C_0 is the initial concentration of the contaminated liquid (mg/L), Ce is the concentration of the contaminated liquid after the adsorbent reaches adsorption equilibrium (mg/L), m is the mass of the adsorbent (g), and V is the volume of the contaminated liquid (L).

2.2.3 Pot trials

To evaluate the phytotoxicity and remediation effectiveness of the amended soil in practical environments, pot trials were conducted using ryegrass (Lolium perenne L.) as a model plant. The

experiment comprised six treatments: non-amended soil (CK), CK + P-K fertilizer (EK1), CK + heavy metals (EK2), amendment only (EK3), amendment + P-K fertilizer (EK4), and amendment + heavy metals (EK5). Each treatment was performed in quintuplicate. The pots were incubated under freeze-thaw cycles, with regular irrigation to maintain optimal soil moisture. Upon seedling stabilization, germination and survival rates were determined. Plant height was recorded at 7, 14, 21, and 28 days post-emergence, and fresh weight was measured at day 28. All data are presented as mean ± standard deviation (SD). Statistical significance was assessed via one-way analysis of variance (ANOVA), with significance defined at $p < 0.05$.

2.3 Characterization

Soil bulk density was determined using the core cutter method. Cation exchange capacity (CEC) was measured using a Kjeldahl nitrogen analyzer (HD-KN60, Horde, China). The phase structure of the materials was characterized by X-ray diffraction (XRD; DX-2700, Bruker, Germany). The micromorphology of the materials was observed via scanning electron microscopy (SEM; Inspect F50, FEI, USA). The concentrations of Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+} in the aqueous solutions were accurately determined using inductively coupled plasma optical emission spectrometry (ICP-OES; iCAP 7000, Thermo Fisher Scientific, USA).

2.4 Adsorption kinetics and isotherm studies

2.4.1 Adsorption kinetic studies

The quasi-first-order dynamics and quasi-second-order dynamics models were utilised in this experiment to fit the experimental data, with equations shown in equations (3) and (4):

$$\ln(q_e - q_t) = \ln q_e - K_1 t \quad (3)$$

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \quad (4)$$

Where q_t represents the adsorbent's unit adsorption capacity at time t(mg/g), and q_e represents the equilibrium adsorption amount (mg/g) when the adsorbent reaches adsorption equilibrium. k_1 and k_2 correspond to the rate constants for adsorption in the quasi-first and quasi-second order equations, respectively.

2.4.2 Adsorption isotherm model

In this experiment, the Langmuir and Freundlich models were used to fit the experimental data with the following equations (5) and (6):

$$\frac{C_e}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m} \quad (5)$$

$$\lg q_e = \frac{1}{n} \times \lg C_e + \lg K_F \quad (6)$$

Where q_e (mg/g) is the unit adsorption capacity when the adsorbent is in equilibrium, and q_m (mg/g) is the sample's saturation adsorption capacity. In the Langmuir and the Freundlich adsorption isotherm models, the adsorption equilibrium constants are denoted by K_L and K_F, respectively. n represents the ease with which adsorption occurs on the adsorbent; when $0.1 < 1/n < 0.5$, adsorption is easy to occur; when $1/n > 2$, adsorption is difficult to occur.

3. Results and discussion

3.1 Influence of the Composite Amendment on Soil Properties

Based on the orthogonal optimization experiments, the optimal mass ratio of the composite amendment was determined to be diatomite: biochar: gypsum: magnesium hydroxide: soil = 5:6:1:1.45:103. This formulation exhibited superior efficacy in improving soil properties (Table 1). Compared with the CK group, the EK treatment significantly enhanced the immobilization of heavy metals, with comprehensive adsorption capacity and efficiency increasing by 185.45% and 176.32%, respectively. Furthermore, the amendment effectively improved soil water saturation, average daily evaporation, and physicochemical properties of the soil. Notably, the system maintained the soil pH at a near-neutral level (6.9) while simultaneously increasing phosphorus and potassium retention capacities by 20.34% and 100.7%, respectively. These results confirm the potential of this formulation for the synergistic improvement of water/nutrient retention and heavy metal immobilization in alpine-arid soils.

The SEM images in Fig 2 visually characterize the microstructural evolution of the materials. The individual raw materials exhibited typical morphological features: disk-like pores for diatomite (Fig 2a), stacked plates for gypsum (Fig 2b), rough porous surfaces for biochar (Fig 2c), and regular lamellar structures for magnesium hydroxide (Fig 2d). Comparative analysis revealed that following the incorporation of the amendment, the EK group displayed increased particle size, enhanced surface roughness, and higher soil granularity, resulting in a more complex heterogeneous composite structure (Fig 2e-f). This confirms the successful attachment of the amendment components onto the soil matrix surface. The XRD patterns in Fig 3 illustrate the crystalline phase characteristics. As shown in Fig 3b, the EK group exhibited intensified diffraction peaks at $2\theta = 21°$, 27°, and 28° compared to the CK group, with the primary diffraction peaks corresponding precisely to the standard SiO_2 card (PDF#83-2466). This indicates that the Tibetan soil matrix is dominated by a quartz crystal phase and that the addition of the amendment did not alter the macro-crystalline structure of the soil, suggesting that the components primarily form a stable system through surface complexation. Combined SEM and XRD results confirm the successful integration of gypsum, diatomite,

biochar, and magnesium hydroxide with the soil matrix, thereby establishing a robust composite remediation system.

Table 1 Amelioration effects of optimized formulations on soil properties

	Heavy metal immobilization		Water index		Physicochemical properties of the soil				
	Qe (mg/g)	R (%)	Water saturation (g)	Daily Evaporation (g/day)	CEC (cmol/kg)	BD (g/cm³)	pH	P-retention (mg/g)	K-retention (mg/g)
CK	1.285	24.4	35.09	3.6	7.33	1.55	7.22	0.59	0.135
EK	3.668	67.4	40.25	2.76	10.62	1.18	6.9	0.71	0.275
Percentage	↑ 185.45%	↑ 176.32%	↑ 14.71%	↓ 23.33%	↑ 44.88%	↓ 23.87%	↓ 4.43%	↑ 20.34%	↑ 100.7%

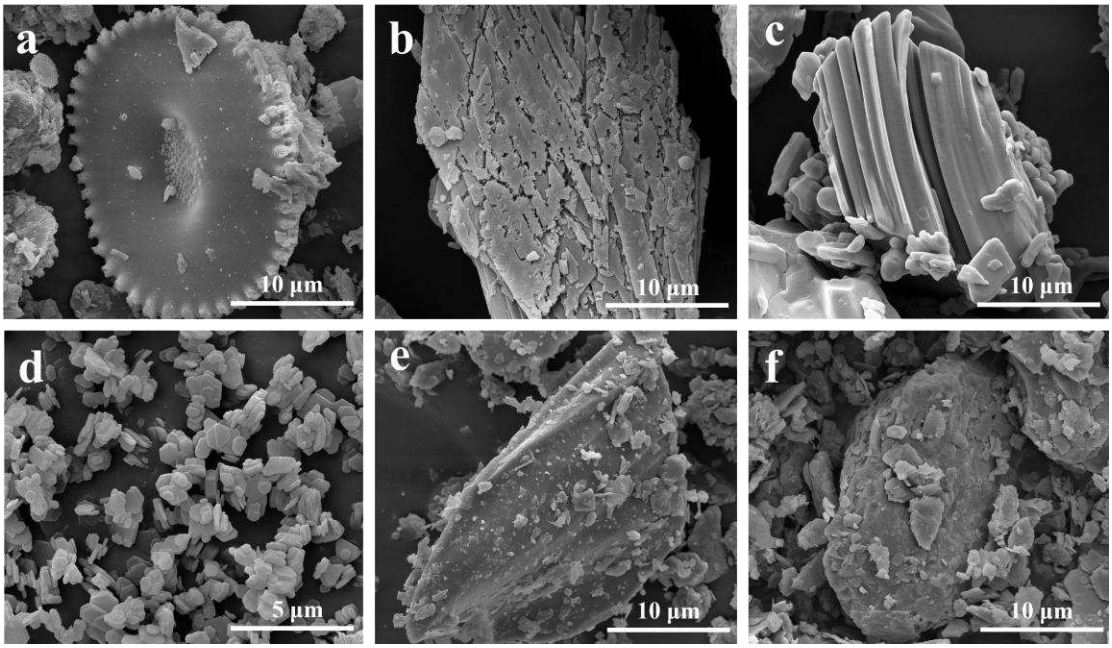


Fig 2 SEM (a: diatomite, b: biochar, c: gypsum, d: magnesium hydroxide, e: CK, f: EK)

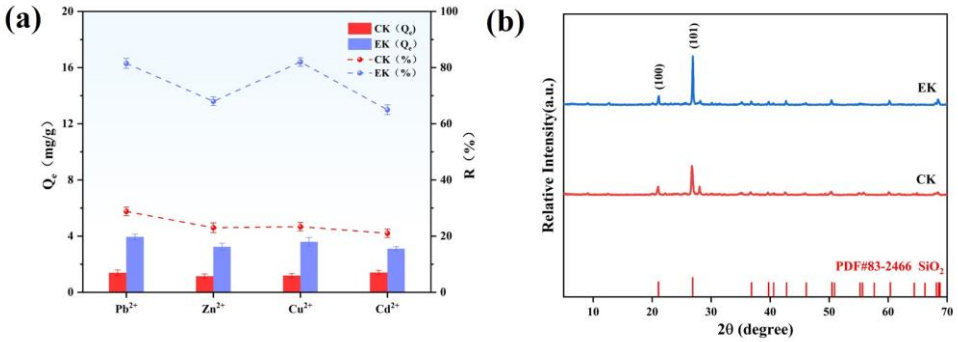


Fig 3 (a: Adsorption efficiency of different components for single-metal ions, b: XRD patterns of different components)

3.2 Adsorption Behavior of the Amended Soil toward Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+} in a Multi-metal System under Freeze-Thaw Conditions

3.2.1 Adsorption performance of the amended soil in the multi-metal system

As shown in (Fig 4a), in a competitive system where multiple ions coexist, the EK-treated group exhibited significantly enhanced adsorption capacities and efficiencies for all four heavy metal ions compared to the CK group after exposure to freeze-thaw cycles. The Q_e values for Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+} in the EK group reached approximately 3.94, 2.92, 4.31, and 2.80 mg/g, respectively, representing a 2 to 3-fold increase over those of the CK group (1.39, 1.15, 1.19, and 1.45 mg/g). Concurrently, the adsorption efficiencies for the four ions in the EK group were substantially higher than those in the CK group. Pb^{2+} exhibited the highest removal efficiency (approximately 81.5%), followed by Cu^{2+} (approximately 70.5%), while Zn^{2+} and Cd^{2+} showed comparable efficiencies (approximately 58%). In contrast, the adsorption efficiencies of the CK group remained at a low level (20%–30%) for all ions, with minimal variation in adsorption performance among them. The adsorption order for the ions was $Cu^{2+} > Pb^{2+} > Zn^{2+} > Cd^{2+}$, which is primarily attributed to variations in metal ionic radius, hydrated ionic radius, electronegativity, and hydrolysis constants (Lee et al., Lee, H. S., & Shin, H. S. (2021). Competitive adsorption of heavy metals onto modified biochars: Comparison of biochar properties and modification methods. *Journal of Environmental Management*, *299*, Article 113651. https://doi.org/10.1016/j.jenvman.2021.113651).

3.2.2 Effect of initial concentration of the multi-metal solution

To elucidate the adsorption mechanism of heavy metal ions by EK, the experimental data were fitted using the Langmuir and Freundlich isotherm models (Fig 4b, c and Table 2). The results demonstrated that after freeze-thaw treatment, the adsorption behavior of Pb^{2+} and Zn^{2+} on EK conformed better to the Freundlich model, with correlation coefficients (R^2) R^2)of 0.987 and 0.993, respectively, which were significantly higher than those obtained from the Langmuir model (0.960 and 0.949). This indicates that under freeze-thaw stress, the adsorption of Pb^{2+} and Zn^{2+} onto the EK surface is primarily governed by multilayer adsorption on heterogeneous surfaces (Ayawei et al., Ayawei, N., Ebelegi, A. N., & Wankasi, D. (2017). Modelling and interpretation of adsorption isotherms. *Journal of Chemistry*, *2017*, Article 3039817. https://doi.org/10.1155/2017/3039817). Furthermore, the 1/n values for both ions fell within the range of 0–1 (Pb^{2+}: 0.644; Zn^{2+}: 0.714), suggesting that the adsorption of Pb^{2+} and Zn^{2+} onto EK is favorable, spontaneous, and readily occurs. The lower 1/n value for Pb^{2+} indicates a higher adsorption affinity. The Freundlich constant

(k_f), related to adsorption capacity, was higher for Pb^{2+} (0.785) than for Zn^{2+} (0.642), further corroborating the superior adsorption performance for Pb^{2+}, which is consistent with the higher removal efficiency observed in the multi-metal system. The material exhibits a more pronounced adsorption affinity and favorability for Pb^{2+}, while the theoretical monolayer adsorption capacity for Zn^{2+} is slightly higher. The adsorption processes for both ions are spontaneous and feasible, providing a robust theoretical foundation for the application of EK in the remediation of multi-metal-contaminated soils in alpine regions.

3.2.3 Effect of adsorption time

To elucidate the rate-controlling mechanisms for the adsorption of heavy metal ions from multi-metal solutions by EK under freeze-thaw conditions, the experimental data were fitted using pseudo-first-order and pseudo-second-order kinetic models (Fig 4d, e). The fitting parameters (Table 2) indicated that the adsorption kinetics of Pb^{2+} exhibited an excellent fit to the pseudo-second-order model (R^2=0.982), which was superior to that of the pseudo-first-order model (R^2=0.979). This result strongly suggests that the adsorption of Pb^{2+} by EK is primarily governed by chemisorption, where the adsorption rate is limited by the sharing of electrons or the formation of valence bonds (such as complexation or ion exchange) between the surface functional groups of the adsorbent and the metal ions (Azam et al., Azam, M., Wabaidur, S. M., Khan, M. R., Al-Resayes, S. I., & Islam, M. S. (2022). Heavy metal ions removal from aqueous solutions by treated Ajwa date pits: Kinetic, isotherm, and thermodynamic approach. *Polymers*, *14*(5), Article 914. https://doi.org/10.3390/polym14050914). Conversely, the adsorption behaviors of Zn^{2+}, Cu^{2+}, and Cd^{2+} were better described by the pseudo-first-order kinetic model (R^2=0.995, 0.928, R^2=0.995, 0.928, and 0.932, respectively), with coefficients exceeding those of the corresponding pseudo-second-order model. This indicates that the adsorption of Zn^{2+}, Cu^{2+}, and Cd^{2+} in the multi-ion competitive system is predominantly controlled by physisorption or diffusion mechanisms (Chen et al., Chen, D., Li, H., Tan, J., Du, D., & Zhan, W. (2024). Stepwise extraction of Fe, Si fromcopper slag and self-assembly synthesis of microspheres for As(V) removal: Resource transformation and environmental governance. *Chemical Engineering Journal*, *490*, Art- icle 151860. https://doi.org/10.1016/j.cej.2024.151860). In conjunction with the aforementioned ionic radius analysis, it is inferred that the smaller-radius ions (Zn^{2+}, Cu^{2+}, and Cd^{2+}) primarily migrate into the interlayer spaces of diatomite and the micropores of biochar via boundary layer or pore diffusion; consequently, their adsorption rates are predominantly determined by the solute concentration gradient and diffusion resistance rather than the chemical reaction rate at the surface (Senthil Kumar et al., Senthil Kumar, P., Nair, A. S., Ramaswamy, A., & Saravanan, A. (2018). Nano-zero valent iron impregnated cashew nut shell: A solution to heavy metal contaminated water/wastewater. *IET Nanobiotechnology*, *12*(5), 591–599. https://doi.org/10.1049/iet-

nbt.2017.0264).

3.2.4 Effect of initial solution pH

The initial pH value not only regulates the electrochemical properties of the adsorbent surface but also acts as a critical environmental factor governing the mobility of heavy metals in mining areas. As illustrated in (Fig 4f), the adsorption efficacy of EK toward heavy metals exhibited a strong pH-dependence following freeze-thaw treatment. As the pH increased from 3.0 to 7.0, the adsorption efficiencies for Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+} increased significantly. The adsorption of Zn^{2+}, Cu^{2+}, and Cd^{2+} was more sensitive to pH changes in the range of 3.0–5.0, whereas the influence was less pronounced between 5.0 and 7.0. At pH 5.0, the adsorption efficiencies for Zn^{2+}, Cu^{2+}, and Cd^{2+} increased from 47%, 53%, and 62% to 70%, 93%, and 87%, respectively. Furthermore, precipitate formation was observed in the solution as the pH increased from 6.0 to 7.0 (Tang et al., Tang, X. F., Wu, Y., Han, L. B., Lan, Z., & Rong, X. P. (2022). Characteristics of heavy metal migration in farmland. *Environmental Earth Sciences*, *81*(12), Article 338. https://doi.org/10.1007/s12665-022-10429-2). Mechanistic analysis indicates that in the low pH range, the decreasing concentration of H^{+} facilitates the deprotonation of -OH and -COOH groups on the mineral surfaces, exposing negatively charged sites that effectively capture highly active free metal ions (Kushwaha et al., Kushwaha, A., Rani, R., & Patra, J. K. (2020). Adsorption kinetics and molecular interactions of lead [Pb(II)] with natural clay and humic acid. *International Journal of Environmental Science and Technology*, *17*(3), 1325–1336. https://doi.org/10.1007/s13762-019-02411-6). Simultaneously, the composite pore structure formed by biochar, diatomite, and gypsum exerts optimal synergistic adsorption in this range. Conversely, at higher pH levels, the formation of metal hydroxide precipitates may mask active adsorption sites, coupled with intensified competition from coexisting cations such as Ca^{2+} and Mg^{2+} (Sis et al., Sis, H., & Uysal, T. (2014). Removal of heavy metal ions from aqueous medium using Kuluncak (Malatya) vermiculites and effect of precipitation on removal. *Applied Clay Science*, *95*, 1–8. https://doi.org/10.1016/j.clay.2014.03.018). In conclusion, the optimal pH for the treatment of multi-metal-contaminated solutions by EK is 5.0.

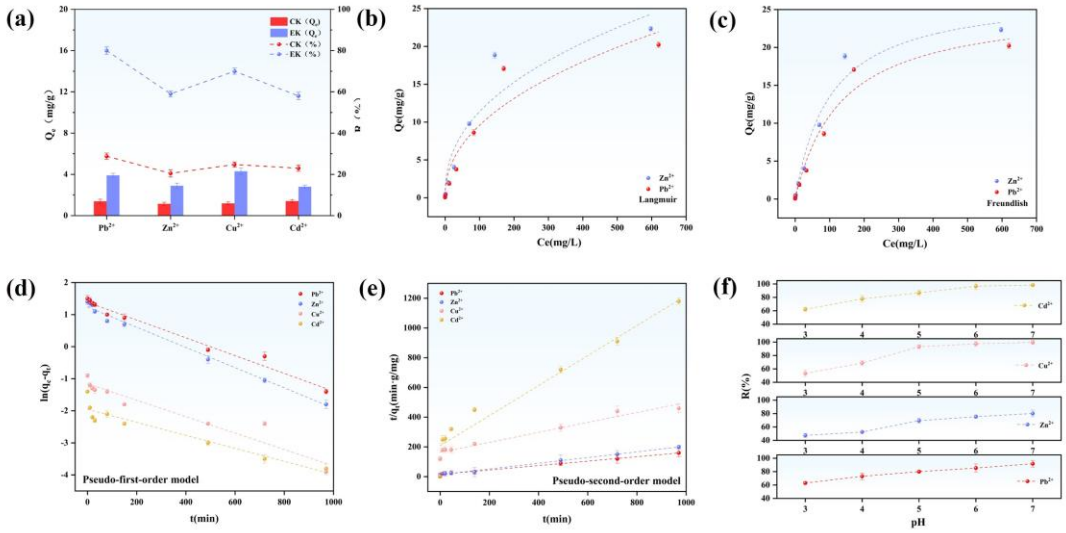


Fig 4 (a: Adsorption efficiency of different components for multi-metal ions, b: Langmuir adsorption isotherm, c: Freundlich adsorption isotherm, d: Pseudo-first-order kinetics, e: Pseudo-second-order kinetics, f: Effect of initial solution pH on the adsorption performance of EK)

Table 2 Adsorption isotherm and kinetic fitting parameters for the adsorption of Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+} from the multi-metal solution by EK

Absorbate	Langmuir model			Freundlich model		
	Q_m(mg/g)	k_l (l/mg)	R^2	1/n	k_f (mg/g)	R^2
Pb^{2+}	22.505	0.257	0.960	0.644	0.785	0.987
Zn^{2+}	20.710	0.302	0.949	0.714	0.642	0.993
Absorbate	Pseudo-first-order model			Pseudo-second-order model		
	k_1 (min^{-1})	Q_e(mg/g)	R^2	k_2(g/mg · min)	Q_e(mg/g)	R^2
Pb^{2+}	0.0032	3.9156	0.979	0.0024	4.5188	0.982
Zn^{2+}	0.0037	3.4165	0.995	0.0029	4.0796	0.985
Cu^{2+}	0.0028	0.2994	0.928	0.0402	2.1164	0.881
Cd^{2+}	0.1448	0.1448	0.923	0.0768	1.0100	0.925

3.3 Promotion of Ryegrass Growth by the Amended Soil

Ryegrass (Lolium perenne L.) is widely utilized as forage in animal husbandry due to its robust cold tolerance, suitability for neutral to slightly alkaline soils, and high content of crude protein, minerals, and trace elements (Lu et al., Lu, X., Chen, X., Vancov, T., Zhu, F., Zhu, W., Hong, L., Yao, Y., Li, P., Wang, W., & Hong, C. (2025). Combined remediation effect of ryegrass-earthworm on heavy metal composite contaminated soil. *Journal of Hazardous Materials*, *483*, Article 138477. https://doi.org/10.1016/j.jhazmat.2025.138477). As shown in (Fig 5a), ryegrass in the CK

group exhibited stunted growth under freeze-thaw conditions, with the most severe inhibition observed in the EK2 group (CK + heavy metals). In contrast, the application of the amendment significantly promoted plant growth in the EK3, EK4, and EK5 groups. Notably, the EK5 group (amendment + heavy metals) demonstrated a marked improvement in growth compared to the EK2 group. The germination and survival rates of ryegrass in the amendment-treated groups (EK3, EK4, and EK5) were significantly higher than those in the non-treated groups (CK, EK1, and EK2), with the EK4 group (amendment + P-K fertilizer) achieving the highest rates of 98% and 100%, respectively (Fig 5b). Fresh weight, serving as an indicator of overall biomass, growth status, and water content, further reflected these trends (Ma et al., Ma, J., Chen, J., Xu, D., Jiang, W., & Wang, C. (2025). Dual cross-modality fusion boosts the RGBD-based lettuce fresh weight estimation. *Computers and Electronics in Agriculture*, *222*, Article 110721. https://doi.org/10.1016/j.compag.2025.110721). The fresh weight of the CK group was 3.26 g/pot, whereas those of the EK3 and EK4 groups reached 4.40 g/pot and 4.68 g/pot, representing increases of 35.0% and 43.56%, respectively. Under heavy metal stress, the fresh weight of the EK2 group decreased by 41.41% compared to the CK group, whereas the EK5 group showed an increase of 19.63% (Fig 5c). The growth trends in plant height were consistent with those of germination rate, survival rate, and fresh weight; the EK3, EK4, and EK5 groups consistently outperformed the non-amended groups, with the EK4 group achieving the maximum average height of 20 cm (Fig 5d). In summary, while heavy metals severely inhibit plant growth, the incorporation of the composite amendment effectively mitigates heavy metal bioavailability, thereby transforming the degraded mining soil into a viable substrate for plant cultivation (Sui et al., Sui, X., Wang, L., Lv, X., Liu, Y., Zhu, Y., Fan, L., & Wang, H. (2025). Influence of composite amendments on the characteristics of sandy soil. *Sustainability*, *17*(17), Article 7619. https://doi.org/10.3390/su17177619).

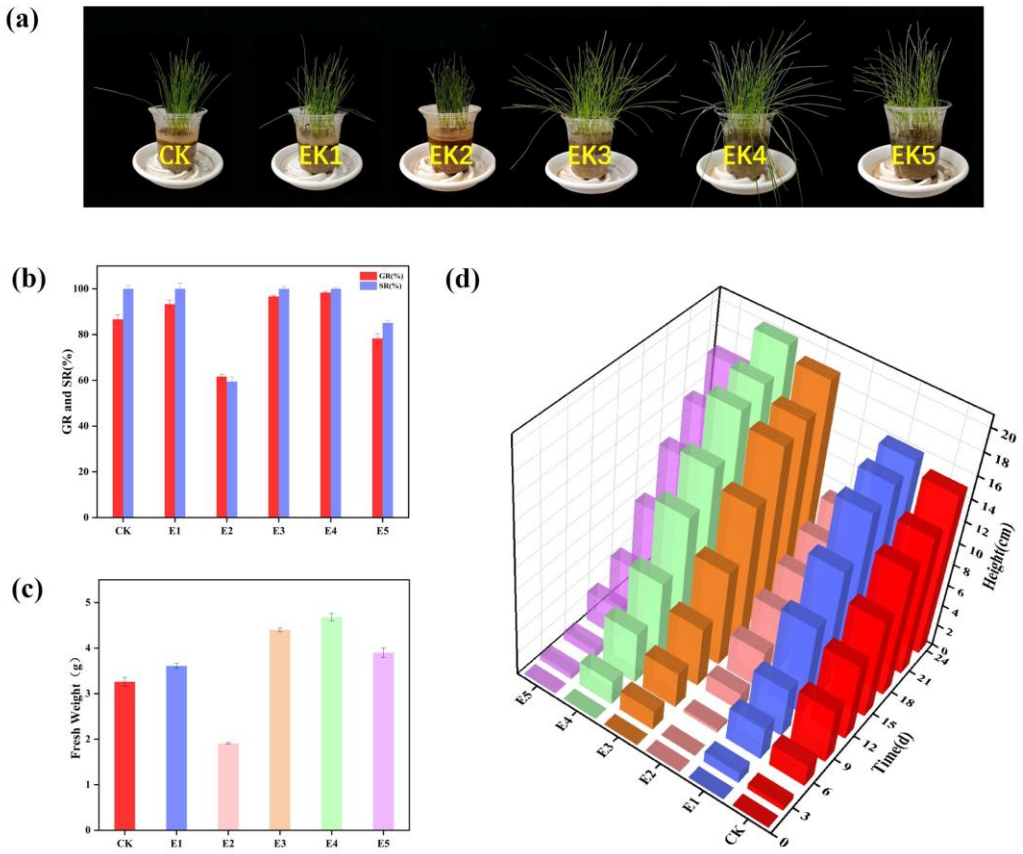


Fig 5 Growth of ryegrass under different cultivation conditions (a: photographs of ryegrass at the maturation stage, b: germination and survival rates, c: fresh weight, d: plant height)

4. Conclusions

This study addresses the critical issues of multi-metal contamination and soil degradation in the alpine-arid Pb-Zn mining regions of the Qinghai-Tibet Plateau. A multifunctional composite amendment capable of soil property amelioration, water and nutrient retention, and heavy metal immobilization was successfully synthesized using locally sourced materials. Through process optimization, physicochemical characterization, mechanistic investigation, and greenhouse pot trials, the following conclusions were drawn:

(1) Based on systematic orthogonal optimization, the optimal mass ratio of the composite amendment was determined to be diatomite: biochar: gypsum: magnesium hydroxide: soil = 5:6:1:1.45:103. This formulation improved soil saturated water capacity and water-holding capacity by 14.71% and 23.33%, respectively, while reducing bulk density by 23.81%. Furthermore, the cation exchange capacity (CEC) increased by 44.88%, and phosphorus and potassium retention capacities were enhanced by 20.34% and 100.7%, respectively, all while maintaining a near-neutral soil pH of 6.9.

(2) In both single and multi-metal (Pb^{2+}, Zn^{2+}, Cu^{2+}, and Cd^{2+}) systems, the amended soil (EK) exhibited a 2- to 3-fold increase in heavy metal adsorption capacity and efficiency compared to the CK group. The removal efficiencies for Pb^{2+} and Cu^{2+} exceeded 70%, while those for Zn^{2+} and Cd^{2+} were approximately 58%. The adsorption of Pb^{2+} and Zn^{2+} conformed to the Freundlich isotherm model, indicating that multilayer adsorption on heterogeneous surfaces is the core mechanism. Kinetic studies revealed that Pb^{2+} immobilization follows a pseudo-second-order model, dominated by chemisorption processes such as surface complexation and precipitation, whereas the immobilization of the smaller-radius ions (Zn^{2+}, Cu^{2+}, and Cd^{2+}) aligns with the pseudo-first-order kinetic model, indicating control by physical diffusion mechanisms. The amendment demonstrated optimal adsorption performance at an initial solution pH of 5.0.

(3) Indoor pot trials confirmed that, under heavy metal stress, the EK5 group (amendment + heavy metals) showed comprehensive growth improvements compared to the non-amended EK2 group. Germination and survival rates increased by 13.20% and 27.91%, respectively, while fresh weight and average plant height increased by 104.19% and 111.11%, respectively. These results indicate that the amendment significantly mitigates heavy metal stress and restores soil fertility, providing essential conditions for vegetation growth in degraded alpine-arid mining areas.

In summary, the multifunctional composite amendment developed in this study provides a robust theoretical foundation and practical engineering material for the comprehensive ecological restoration of degraded soils in the high-altitude, cold, and arid mining regions of the Qinghai-Tibet Plateau.

Declarations：

Ethical Approval

This article does not contain any studies involving human participants or animals performed by any of the authors, and ethical approval is not applicable for this work.

CRediT authorship contribution statement

Jie Zhou: Writing - original draft, Methodology, Visualization, Investigation, Formal analysis, Data curation, Peicong Zhang: Writing - review & editing, Resources. Jinhua Luo: Methodology. Yi Huang: Funding acquisition, Methodology. Jialin He: Supervision. Jinshu Zhang: Resources. Yubin Li: Resources. Chengye Yang: Resources.

Funding

This work was supported by the Science and Technology Major Project of the Xizang Autonomous Region of China (Grant No. XZ202201ZD0004G06) and the Everest Scientific Research Program (Grant No. 80000-2024ZF11421).

Data availability

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

Availability of data and materials

Supplementary data are not required for this article, and all data supporting the findings are fully presented within the main manuscript.

Reference

Anastopoulos, I., Ahmed, M. J., Ojukwu, V. E., Danish, M., Stylianou, M., & Ighalo, J. O. (2024). A comprehensive review on adsorption of Reactive Red 120 dye using various adsorbents. *Journal of Molecular Liquids*, *394*, Article 123719. https://doi.org/10.1016/j.molliq.2023.123719

Ayawei, N., Ebelegi, A. N., & Wankasi, D. (2017). Modelling and interpretation of adsorption isotherms. *Journal of Chemistry*, *2017*, Article 3039817. https://doi.org/10.1155/2017/3039817

Azam, M., Wabaidur, S. M., Khan, M. R., Al-Resayes, S. I., & Islam, M. S. (2022). Heavy metal ions removal from aqueous solutions by treated Ajwa date pits: Kinetic, isotherm, and thermodynamic approach. *Polymers*, *14*(5), Article 914. https://doi.org/10.3390/polym14050914

Bai, X., Zhang, E., Wu, J., Ma, D., Zhang, B., Zhang, C., Tian, F., Zhao, H., & Wang, B. (2024). Effects of different modified materials on soil fungal community structure in saline-alkali soil. *Environmental Science*, *45*(6), 3562–3570. https://doi.org/10.13227/j.hjkx.202306086

Bi, H., Xu, J., Li, K., Li, K., Cao, H., & Zhao, C. (2024). Effects of biochar-coated nitrogen fertilizer on the yield and quality of bok choy and on soil nutrients. *Sustainability*, *16*(4), Article 1659. https://doi.org/10.3390/su16041659

Chen, D., Li, H., Tan, J., Du, D., & Zhan, W. (2024). Stepwise extraction of Fe, Si from copper slag and self-assembly synthesis of microspheres for As(V) removal: Resource transformation and environmental governance. *Chemical Engineering Journal*, *490*, Article 151860. https://doi.org/10.1016/j.cej.2024.151860

Holanda, S. F., Vargas, L. K., & Granada, C. E. (2025). Challenges for sustainable production in sandy soils: A review. *Environment, Development and Sustainability*, *27*(1), 53–66. https://doi.org/10.1007/s10668-023-03894-3

Ding, R., Jin, X., & Liu, G. (2021). Characteristics of diatomite mineral resources in China and analysis of supply and demand situation. *Jilin Geology*, *40*(4), 25–29. https://doi.org/10.3969/j.issn.1001-2427.2021.04.005

Feng, W., Yang, F., Cen, R., Liu, J., Qu, Z., Miao, Q., & Chen, H. (2021). Effects of straw biochar application on soil temperature, available nitrogen and growth of cor-n. *Journal of Environmental Management*, *277*, Article 111331. https://doi.org/10.1016/j.jenvman.2020.111331

Gao, R., Chen, H., Li, C., Liang, X., Hou, X., & Yang, B. (2024). Preparation of diatomite-based porous ceramics and their adsorption properties for Cu^{2+}. *Ceramics International*, *50*(23), 50153–50162. https://doi.org/10.1016/j.ceramint.2024.09.362

Hu, C. (2023). Effect of phosphogypsum on adsorption and desorption characteristics of m-agnesium in loess soil. *Science Technology and Engineering*, *23*(30), 12842–12849. https://doi.org/10.3969/j.issn.1671-1815.2023.30.009

Hu, Z., Wang, C., Li, K., & Zhu, X. (2018). Distribution characteristics and pollution assessment of soil heavy metals over a typical nonferrous metal mine area in Chifeng, Inner Mongolia, China. *Environmental Earth Sciences*, *77*(18), Article 638. https://doi.org/10.1007/s12665-018-7771-1

Huang, C., Huang, M., Hu, G., & Zeng, H. (2020). Influence and attribution of the cascade hydropower station operation on the hydrological regimes in Lhasa River. *Journal of Water Resources and Water Engineering*, *31*(5), 62–69. https://doi.org/10.11705/j.issn.1672-643X.2020.05.10

Huang, P., Fang, Z., Yu, H., Zhang, F., & Huang, J. (2023). Effects of combined application of different amendments on physicochemical properties of alkalized soil and growth of Lycium barbarum in Hetao Irrigation District. *Agricultural Research in the Arid Areas*, *41*(5), 12–19. https://doi.org/10.7606/j.issn.1000-7601.2023.05.13

Jia, W., Li, J., Shen, C., Li, G., Li, H., Fan, G., Zhou, G., & Cao, Y. (2025). Research advances in phosphogypsum flotation purification: Current status and prospects. *Separation and Purification Technology*, *354*, Article 129244. https://doi.org/10.1016/j.seppur.2024.129244

Kushwaha, A., Rani, R., & Patra, J. K. (2020). Adsorption kinetics and molecular interactions of lead [Pb(II)] with natural clay and humic acid. *International Journal of Environmental Science and Technology*, *17*(3), 1325–1336. https://doi.org/10.1007/s13762-019-02411-6

Lee, H. S., & Shin, H. S. (2021). Competitive adsorption of heavy metals onto modified biochars: Comparison of biochar properties and modification methods. *Journal of Environmental Management*, *299*, Article 113651. https://doi.org/10.1016/j.jenvman.2021.113651

Li, H., Gao, Y., Zheng, Y., Li, N., Zhang, L., & Liu, Z. (2023). Adsorption performance of cross-linked starch loaded magnesium hydroxide composite for Cu^{2+}. *Industrial Water Treatment*, *43*(11), 161–166. https://doi.org/10.19965/j.cnki.iwt.2022-1165

Li, L., Lei, Y., Chen, Q., Deng, X., Bao, H., Zhaqiong, B., & Sun, G. (2023). Changes of soil total carbon and plant root characteristics during the restoration of alpine desertification grassland in Zoige. *Chinese Journal of Ecology*, *42*(2), 282–290. https://doi.org/10.13292/j.1000-4890.202302.011

Li, Z., Chen, K., Zhai, S., Yang, L., Yu, T., Yuan, H., Zeng, B., Yang, L., Qi, F., & Zhu, H. (2024). Preparation of biochar from anaerobic digested sludge for enhancement of sludge dewatering. *Chemosphere*, *362*, Article 142687. https://doi.org/10.1016/j.chemosp - here.2024.142687

Li, Z., Wang, G., Li, Z., Wang, H., Guo, X., Zhao, Q., & Nan, Y. (2021). Current situation and development countermeasures of diatomite utilization in China. *China Non-Metallic Minerals Industry*, *23*(3), 1–5. https://doi.org/10.3969/j.issn.1007-9386.2021.03.001

Lin, H., Wang, Z., Liu, C., & Dong, Y. (2022). Technologies for removing heavy metal f-rom contaminated soils on farmland: A review. *Chemosphere*, *305*, Article 135457. https://doi.org/10.1016/j.chemosphere.2022.135457

Liu, X., Liao, C., Lin, L., Gao, H., Zhou, J., Feng, Z., & Lin, Z. (2020). Research progress in the environmental application of magnesium hydroxide nanomaterials. *Surfaces and Interfaces*, *21*, Article 100701. https://doi.org/10.1016/j.surfin.2020.100701

López, J. E., Arroyave, C., Aristizábal, A., Almeida, B., Builes, S., & Chavez, E. (2022). Reducing cadmium bioaccumulation in Theobroma cacao using biochar: Basis for scaling-up to field. *Heliyon*, *8*(6), Article e09790. https://doi.org/10.1016/j.heliyon.2022.e09790

Lu, X., Chen, X., Vancov, T., Zhu, F., Zhu, W., Hong, L., Yao, Y., Li, P., Wang, W., & Hong, C. (2025). Combined remediation effect of ryegrass-earthworm on heavy metal composite contaminated soil. *Journal of Hazardous Materials*, *483*, Article 138477. https://doi.org/10.1016/j.jhazmat.2025.138477

Ma, J., Chen, J., Xu, D., Jiang, W., & Wang, C. (2025). Dual cross-modality fusion boosts the RGBD-based lettuce fresh weight estimation. *Computers and Electronics in Agriculture*, *222*, Article 110721. https://doi.org/10.1016/j.compag.2025.110721

Montagnoli, A., Baronti, S., Alberto, D., Chiatante, D., Scippa, G. S., & Terzaghi, M. (2021). Pioneer and fibrous root seasonal dynamics of Vitis vinifera L. are affected by biochar application to a low fertility soil: A rhizobox approach. *Science of the Total Environment*, *751*, Article 141455. https://doi.org/10.1016/j.scitotenv.2020.141455

Park, B. J., Nam, S. H., Jeong, S. S., Yoon, J.-H., Kirkham, M. B., Yang, J. E., & Kim, H. S. (2026). Valorization of phosphogypsum into carbon-neutral lime for soil lead i-mmobilization. *Environmental Technology & Innovation*, *42*, Article 104879. https://doi.org/10.1016/j.eti.2026.104879

Punia, B. (2021). Role of temperature, wind, and precipitation in heavy metal contaminatio -n at copper mines: A review. *Environmental Science and Pollution Research*, *28*(4), 4 056–4072. https://doi.org/10.1007/s11356-020-11580-8

Qi, J., Zhu, H., Zhou, P., Wang, X., Wang, Z., Yang, S., Yang, D., & Li, B. (2023). Application of phosphogypsum in soilization: A review. *International Journal of Environmental Science and Technology*, *20*(9), 10449–10464. https://doi.org/10.1007/s13762-023-04783-2

Senthil Kumar, P., Nair, A. S., Ramaswamy, A., & Saravanan, A. (2018). Nano-zero valent iron impregnated cashew nut shell: A solution to heavy metal contaminated water/wastewater. *IET Nanobiotechnology*, *12*(5), 591–599. https://doi.org/10.1049/iet-nbt.2017.0264

Sis, H., & Uysal, T. (2014). Removal of heavy metal ions from aqueous medium using Kuluncak (Malatya) vermiculites and effect of precipitation on removal. *Applied Clay Science*, *95*, 1–8. https://doi.org/10.1016/j.clay.2014.03.018

Song, M., Zhong, K., & Bao, X. (2019). Study on ore fabric of the Mengya lead-zinc deposit in Jiali County, Tibet. *West-China Exploration Engineering*, *31*(12), 108–111. https://doi.org/10.3969/j.issn.1004-5716.2019.12.051

Sui, X., Wang, L., Lv, X., Liu, Y., Zhu, Y., Fan, L., & Wang, H. (2025). Influence of composite amendments on the characteristics of sandy soil. *Sustainability*, *17*(17), Article 7619. https://doi.org/10.3390/su17177619

Tang, X. F., Wu, Y., Han, L. B., Lan, Z., & Rong, X. P. (2022). Characteristics of heavy metal migration in farmland. *Environmental Earth Sciences*, *81*(12), Article 338. https://doi.org/10.1007/s12665-022-10429-2

Wang, L., Wu, Q., & Jiang, G. (2020). The effect of desertification on frozen soil on the Qinghai-Tibet plateau. *Science of the Total Environment*, *711*, Article 134640. https://doi.org/10.1016/j.scitotenv.2019.134640

Xia, H., Kong, W., Liu, L., Lin, K., & Li, H. (2021). Effects of harvest time and desalination of feedstock on Spartina alterniflora biochar and its efficiency for Cd2+ removal from aqueous solution. *Ecotoxicology and Environmental Safety*, *207*, Article 111309. https://doi.org/10.1016/j.ecoenv.2020.111309

Yang, Y., Shi, L., Zhang, T., Guo, X., Wang, Y., & Chen, G. (2019). Research on geological environment problems and prevention measures of mineral resources development in plateau alpine canyon areas: A case study of Jiama and Yulong copper mines in Tibet. *Acta Geologica Sichuan*, *39*(6), 394–398. https://doi.org/10.3969/j.issn.1006-0995.2019.S1.019

Yin, Y., Wang, X., Hu, Y., Li, F., & Cheng, H. (2023). Soil bacterial community structure in the habitats with different levels of heavy metal pollution at an abandoned polymetallic mine. *Journal of Hazardous Materials*, *442*, Article 130063. https://doi.org/10.1016/j.jhazmat.2022.130063

Zhang, J., Li, C., Jia, Z., Liu, X., & Meng, M. (2022). Application of functional microorganisms in ecological restoration of abandoned mines. *Journal of Nanjing Forestry University (Natural Sciences Edition)*, *46*(6), 146–156. https://doi.org/10.12302/j.issn.1000-2006.202206012

Zhu, J., Liu, J., Fang, Y., Wu, Z., & Zhang, Y. (2025). Adsorption performance and mechanism of Cd in aqueous solution by modified diatomite. *New Chemical Materials*, *53*(3), 203–209. https://doi.org/10.19817/j.cnki.issn1006-3536.2025.03.031