https://doi.org/10.17221/503/2025-PSE

Biochar combined with hyperaccumulators: a strategy for remediation of heavy metal composite pollution in mining areas

Tingting Cao[1,2,3,4], Wei Wang[1,2,3], Jian Wang[4], Jinbin Li[4], Xubo Sun[4], Yan Xu[4]*

[1]School of Water and Environment, Chang'an University, Xi'an, P.R. China
[2]Key Laboratory of Subsurface Hydrology and Ecological Effects in Arid Region of the Ministry of Education, Chang'an University, Xi'an, P.R. China
[3]Key Laboratory of Eco-hydrology and Water Security in Arid and Semi-arid Regions of Ministry of Water Resources, Chang'an University, Xi'an, P.R. China
[4]Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd. Xi'an, P.R. China

Citation: Cao T.T., Wang W., Wang J., Li J.B., Sun X.B., Xu Y. (2026): Biochar combined with hyperaccumulators: a strategy for remediation of heavy metal composite pollution in mining areas. Plant Soil Environ., 72: 239–258.

Abstract: In pursuit of a low-cost, pollution-free, and scalable technology for remediating heavy metal pollution in mining areas, this study examines a gold mining area with heavy metal pollution (Cd, Pb, and Hg) and employs soil replacement, biochar passivation, and a combination of hyperaccumulators for the remediation. Results show that both soil replacement and the application of biochar significantly reduce the effective content of these three heavy metals, with pig manure biochar demonstrating superior passivation effects on Pb and Hg compared to fruitwood biochar. Combining biochar with hyperaccumulators leads to better results than using either method alone. The combined approach achieved maximum reductions of 69.8, 70.1, and 56.0% for Cd, Pb, and Hg, respectively. The application of biochar improves the originally coarse soil structure, with maximum increases in organic carbon, available potassium, available phosphorus, and total nitrogen under different treatments being 6.26 times, 4.66 times, 4.04 times, and 3.21 times, respectively. Biochar anchors heavy metals around roots, while hyperaccumulators utilise their excellent stress-resistant physiological characteristics to thrive in nutrient-deficient soil enriched with biochar, thereby absorbing the heavy metals anchored by biochar. The synergy of biochar and hyperaccumulators enhances their individual effectiveness, showing promise for remediating polluted mining areas.

Keywords: biochar fixation; anchoring; enrichment and transport; combined remediation technology; soil remediation synergy

Mine waste rocks often contain various chemical elements, including arsenic (As), lead (Pb), zinc (Zn), mercury (Hg), cadmium (Cd), copper (Cu), cobalt (Co), and nickel (Ni), leading to compound pollution in mining areas represented by multiple heavy metal elements (Qin et al. 2021, Zeng et al. 2022). Heavy metal contamination in soil in these regions is a primary factor contributing to the deterioration of soil ecological quality, leading to excessive heavy metal levels in crops and posing risks to human health. According to statistics from the National Mine Geological Environment Survey (NMGES), the recovery and treatment rate in China's mining areas is only 12.8% (Liu et al. 2024b). Currently, identify-

---

Supported by the Shaanxi Agricultural Development Group Co., Ltd, China, Project No. NFJC2025-27; by the Technology Innovation Center for Land Engineering and Human Settlements, Shaanxi Land Engineering Construction Group Co., Ltd, and by the Xi'an Jiaotong University, China, Project No. 2024WHZ0230.

ing suitable methods for remediating heavy metal-contaminated soil in mining areas remains a pressing and challenging issue in the field of environmental science. An analysis of heavy metal remediation technologies reveals that the removal principles primarily consist of two types of approaches. The first involves altering the forms in which heavy metals occur to reduce their available concentrations and convert them into a more stable residual state, thereby decreasing their bioavailability (Song et al. 2022). The second approach employs various physical, chemical, and biological technologies to extract heavy metals from the soil, ultimately aiming to diminish their presence (Eid and Shaltout 2016). Engineering remediation technologies primarily encompass methods such as soil replacement, guest soil application, and deep plowing (Shi et al. 2023b). These techniques necessitate considerable effort and labour and are primarily applicable to areas with limited soil contamination. Physical remediation technologies, on the other hand, involve separating or removing pollutants from soil through physical processes, with common methods including electro-remediation and thermal treatment (Nejad et al. 2017). However, this technology requires complex control processes and high energy consumption, restricting its application (Huang et al. 2024). Additionally, the high temperature can destroy soil nutrients and microorganisms. Chemical remediation methods are classified as fixation and leaching (Fu et al. 2021). The fixation method involves passivating heavy metals in the soil to reduce their biological availability (Yang et al. 2020). However, this technology is not robust, as environmental changes can cause the solidified heavy metals to revert to more bioavailable forms (Chen et al. 2023a). Conversely, chemical leaching is highly efficient but requires a substantial amount of eluent, resulting in high costs and the generation of waste elution liquids, which limits its application (Liu et al. 2021). Bioremediation techniques include phytoremediation and microbial remediation (Sinduja et al. 2023, Mohanty and Selvaraj 2025). Phytoremediation employs plant fixation and extraction methods to absorb and translocate heavy metals from the soil into plant tissues, effectively removing these contaminants. Nevertheless, this approach is characterised by a prolonged remediation timeline (Eid and Shaltout 2016, Mohanty and Selvaraj 2025).

In summary, the heavy metal remediation technologies employed across various mining regions have certain limitations. There are many challenges to the application of remediation methods, such as high costs, inconsistent effectiveness, and difficulties in large-scale implementation (Liu et al. 2021, Guo et al. 2022, Shi et al. 2023a). Heavy metals are significant pollutants that pose considerable environmental risks and are challenging to remove once they contaminate the soil (Penido et al. 2019, Padhi et al. 2024). Evaluating the presence of heavy metals in soil is crucial for implementing effective technical measures to treat and rehabilitate the soil environment. This study aims to investigate stable and easily applicable heavy metal remediation technologies in mining areas. Based on the environmental conditions in the mining area, this study proposes a remediation strategy for the complex contamination by heavy metals. This strategy incorporates soil replacement and the use of biochar, derived from the carbonisation of solid waste, as a passivator, in conjunction with hyperaccumulators.

MATERIAL AND METHODS

Study area and method. This study investigated slag collected from a gold mining area in Tongguan County, Weinan City, Shaanxi Province, China. Its specific location is shown in Figure 1. Slag samples were obtained from the local mining enterprise to analyse their heavy metal content and assess the extent of soil pollution in the area. The site investigation followed a systematic random sampling approach, in accordance with the "Technical Guidelines for Soil Pollution Risk Management, Control and Remediation Monitoring for Construction Land" (HJ 25.2-2019).

To explore potential remediation strategies, the collected slag was thoroughly mixed with surrounding farmland soil at a 1 : 2 mass ratio to prepare a composite soil suitable for cultivation. The farmland soil in the study area is classified as Cinnamon soil, corresponding to Calcic Luvisols according to the FAO soil classification system. Two types of carbon materials – fruit wood biochar and pig manure biochar – were applied to the composite soil as passivating agents. Furthermore, four herbaceous plant species known for their heavy metal accumulation capabilities were selected for joint phytoremediation: alfalfa (*Medicago sativa* L., cv. Zhongmu No. 1), perennial ryegrass (*Lolium perenne* L., cv. Medal), showy stonecrop (*Hylotelephium spectabile* (Boreau) H. Ohba, cv. Spectacular), and black nightshade (*Solanum nigrum* L., var. *nigrum*). Furthermore, as per standard botanical nomenclature conventions,

https://doi.org/10.17221/503/2025-PSE

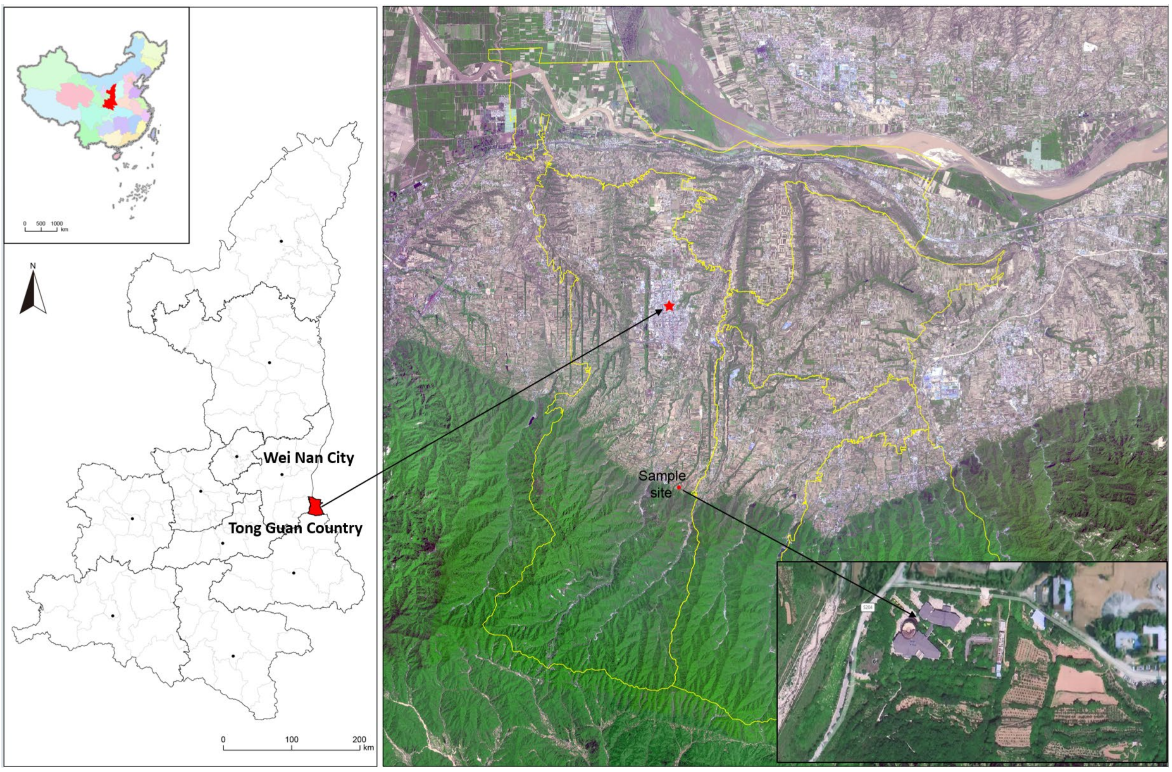

Figure 1. Location map of the mining area

in all subsequent appearances within the main text, figures, and tables, these plant names have been appropriately abbreviated to their italicised initial and specific epithet (*M. sativa*, *L. perenne*, *H. spectabile*, and *S. nigrum*) to ensure conciseness.

Experiments. Heavy metal pollution in the mining area was assessed using site investigation methods, while the soil remediation plan was implemented through pot experiments. The slag from the mining area and the uncontaminated soil from the local farmland were collected and brought back to the laboratory. After removing weeds, stones, and roots, the samples were passed through a 5 mm sieve for further use. The basic physicochemical properties and particle compositions of the slag, farmland soil, and the two types of biochar (fruit wood and pig manure) are presented in Table 1. *M. sativa*, *L. perenne*, *S. nigrum* and *H. spectabile* seedlings were prepared for planting, along with fruit wood biochar and pig manure biochar for later use. The experiment utilised 230 mm × 210 mm plastic flowerpots, with a soil mixture ratio of 1:2 (slag soil to farmland soil). Each pot contained 2.0 kg of the mixed soil. Based on the growth habits and characteristics of the four crops, *M. sativa*, *L. perenne*, *S. nigrum* were sown directly, while *H. spectabile* was transplanted as seedlings. The seeding amounts were calculated according to the planting density typical for these

Table 1. Basic properties of slag and farmland soil

Category	pH	Organic carbon (g/kg)	Available phosphorus	Available potassium	Total nitrogen (g/kg)	Composition (%)		
			(mg/kg)			< 0.002 mm	0.002~0.05 mm	0.05~2 mm
Slag	7.54	3.64	7.10	19.86	0.02	0.03	4.97	95.00
Farm soil	8.04	7.44	16.32	48.4	0.48	0.97	70.32	28.71
Fruit wood biochar	9.31	710.36	72.35	1 086.85	2.82	0.32	12.36	87.32
Pig manure biochar	9.82	360.57	1 650	3 821.36	26.35	5.41	18.34	76.25

plants in the field: *M. sativa* was sown with 0.50 g of seeds per pot, *L. perenne* with 0.17 g, *S. nigrum* with 0.50 g, and two healthy *H. spectabile* seedlings were transplanted. Approximately 10 days after planting, the *S. nigrum* plants were thinned, leaving two seedlings for testing. The experimental design included six groups, each with three replicates, for a total of 90 pots. The potting test setup and treatments are detailed in Table 2. The experiment commenced in April 2023, with harvest scheduled for September 2023. The age of the plant is six months. To accurately simulate the planting and management methods of herbal plants for soil remediation in the mining area, no additional fertilisers were applied; instead, regular watering was conducted to maintain adequate soil moisture for plant growth.

Sample collection and testing. In accordance with the principle of spot placement outlined in the technical guidelines for soil pollution investigation, the plum blossom spot method was employed in the mining area, resulting in the collection of a total of 10 slag soil samples. The sampling depth is 0 cm to 50 cm. The sampling season was spring, and the weather during the sampling period consisted of prolonged sunny days, which minimised the possibility of deviations in results caused by concentrated rainfall washing. These samples were transported to the laboratory, where they were air-dried and subsequently passed through a 0.149 mm sieve for heavy metal detection and evaluation of the contaminated site. In the greenhouse pot experiment, crops were cultivated for a duration of 5 months before the entire potted plant was harvested. The root soil was collected in a sample bag by gently shaking the root system, labelled accordingly, and returned to the laboratory. The soil samples were air-dried, ground, and passed through 2 mm and 0.149 mm sieves for testing of soil physical and chemical properties, as well as heavy metal analysis. Following the rinsing of plant samples, they were separated into aboveground and underground parts. After natural drying, the samples were placed in an oven, adjusted to 75 °C for 30 min, and then dried to a constant weight at 70 °C. Once dried, the samples were ground and passed through a 0.149 mm sieve before analysis.

Evaluation method of heavy metal pollution in a mining area. In this study, the soil risk screening value for agricultural land, as outlined in the Soil Environmental Quality Risk Control Standard for Agricultural Land Soil Pollution (Trial) (GB 15618-2018), was selected as the basis for evaluation. The degree of heavy metal pollution in the mining area is first analysed using the single-factor pollution index method. Subsequently, the comprehensive pollution index of the mining area is evaluated through the Nemerow comprehensive index method. The pollution degree is categorised according to the levels defined by the Nemerow comprehensive pollution index method. Finally, the ecological risk of the region is assessed using the potential ecological risk index method (Wang et al. 2022b, Chen et al. 2023b, Wei et al. 2023).

Statistical analysis. Two-way analysis of variance (ANOVA) and Fisher's least significant difference (*LSD*) were used to assess the statistical significance of heavy metal concentrations across treatments. Concurrently, Pearson's correlation analysis was used to estimate the relationship between soil and plant heavy metal concentrations. All statistical analyses were conducted using R version 3.3.2 (Vienna, Austria) and Microsoft Excel 2019 (Redmond, USA). A redundancy analysis (RDA) model was constructed using Canoco 5 (Ithaca, USA), a professional ecological statistics software. Systematic correlation analyses were conducted to examine the relationships between soil and plant heavy metal content, soil physicochemical properties, and plant growth characteristics.

Table 2. Test design, treatment and corresponding number

Slag treatment	Plant treatment				
	no plants	*Medicago sativa*	*Lolium perenne*	*Hylotelephium spectabile*	*Solanum nigrum*
Slag	S	S-M	S-L	S-H	S-S
Slag:farm soil (1:2)	SS	SS-M	SS-L	SS-H	SS-S
Slag:farm soil (1:2) with pig manure biochar 5%	SSBP5	SSBP5-M	SSBP5-L	SSBP5-H	SSBP5-S
Slag:farm soil (1:2) with pig manure biochar 10%	SSBP10	SSBP10-M	SSBP10-L	SSBP10-H	SSBP10-S
Slag:farm soil (1:2) with fruit wood biochar 5%	SSBW5	SSBW5-M	SSBW5-L	SSBW5-H	SSBW5-S
Slag:farm soil (1:2) with fruit wood biochar 10%	SSBW10	SSBW10-M	SSBW10-L	SSBW10-H	SSBW10-S

https://doi.org/10.17221/503/2025-PSE

RESULTS

Effect of biochar-hyperaccumulator system on the availability of heavy metals in mining area soil

Effect of a biochar-hyperaccumulator system on Cd in mining-area soil. Figure 2 illustrates that adding farmland soil to S resulted in a significant 28.0% decrease ($P < 0.05$) in the total Cd content of the SS soil, while the available Cd content decreased by 34.0% ($P < 0.05$). Following the application of two types of biochar, the total Cd content in the SSBP5, SSBP10, SSBW5, and SSBW10 treatments significantly decreased by 6.0% to 11.0% ($P < 0.05$) compared to SS, with the available Cd content in these treatments being lower than that in SS, decreasing significantly by 21.0% to 30.0% ($P < 0.05$). Notably, when biochar was used in isolation, there was no significant difference observed in Cd removal based on the type or dosage of biochar. The combination of soil replacement and biochar addition demonstrated a significant short-term effect on Cd remediation in the soil. In the biochar-plant system, Cd removal efficacy exceeded that achieved by simply adding biochar. Under *M. sativa* treatment, the total Cd in the soil of the biochar-plant system significantly decreased by 27.0% to 51.0% ($P < 0.05$) compared to the biochar-only treatment, while the available Cd significantly decreased by 12.9% to 60.4% ($P < 0.05$). Furthermore, the pig manure biochar-*M. sativa* system exhibited superior Cd removal efficacy compared to fruit wood biochar. Under *L. perenne* treatment, the total Cd in the soil of the biochar-plant system significantly decreased by 19.8% to 37.6% ($P < 0.05$) relative to the biochar-only treatment, with the available Cd decreasing significantly by 30.0% to 66.4% ($P < 0.05$).

Under the *H. spectabile* treatment, the total Cd concentration in the soil of the biochar-plant system significantly decreased by 46.2% to 63.8% ($P < 0.05$) compared to the biochar-only treatment, while the available Cd significantly decreased by 35.6% to 60.5% ($P < 0.05$). In the case of *S. nigrum* treatment, the total Cd in the soil of the biochar-plant system significantly decreased by 54.3% to 69.8% ($P < 0.05$) relative to the biochar-only treatment, and the available Cd significantly decreased by 39.4% to 68.9% ($P < 0.05$). The overall effectiveness of the four herbaceous plants in removing Cd from the soil is ranked as follows: *S. nigrum* > *H. spectabile* > *M. sativa* > *L. perenne*. Additionally, the passivation effect of pig manure biochar on Cd is superior to the removal effect of fruit wood biochar.

Effect of biochar-hyperaccumulator system on the Pb in soil in mining areas. Figure 3 illustrates that the addition of farmland soil to S resulted in a significant decrease in total Pb content in SS soil

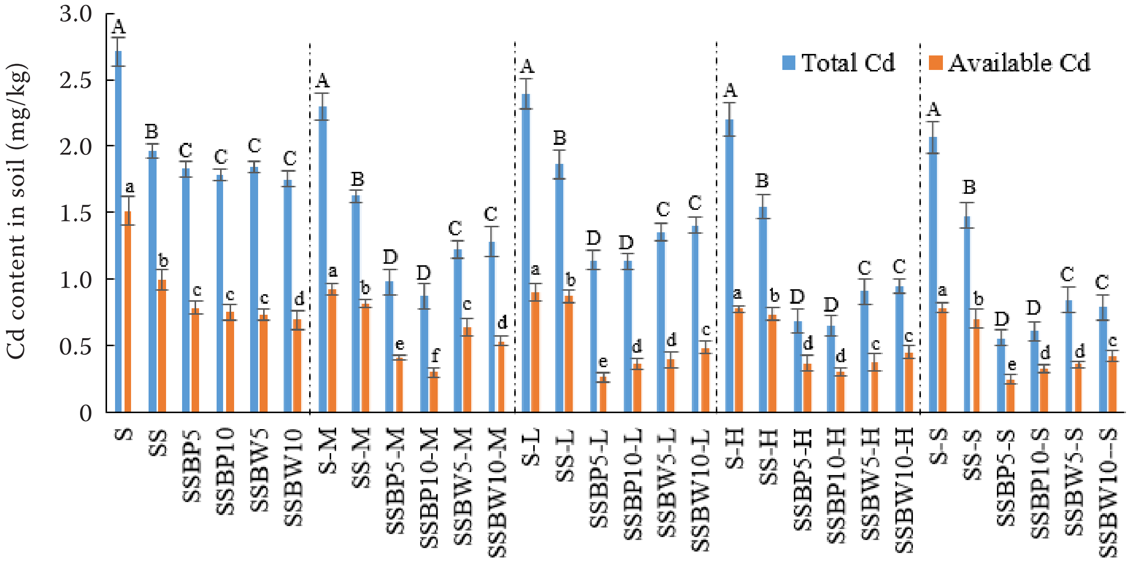

Figure 2. Total and available cadmium (Cd) content in soil in the biochar-plant system. Data are expressed as means ± standard deviation (n = 3). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences in total heavy metal contents among treatments, while different lowercase letters denote significant differences in their available contents

by 5.5% ($P < 0.05$), while the available Pb content in the soil significantly decreased by 11.5% ($P < 0.05$). Following the application of two types of biochar, no significant differences in total Pb content were observed among SSBP5, SSBP10, SSBW5, and SSBW10 soils compared to SS; however, available Pb content decreased by 8.8% to 24.2% ($P < 0.05$) compared to SS. When biochar was used in isolation, the type and dosage of biochar did not significantly affect the removal of total Pb from the soil, but the removal efficiency of available Pb was enhanced. The combination of soil replacement and biochar addition demonstrated a significant short-term effect on the remediation of soil-available Pb. Under the *M. sativa* treatment, the total Pb concentration in the soil of the biochar-plant system significantly decreased by 12.0–22.3% ($P < 0.05$) compared to the biochar-only treatment, while the available Pb significantly decreased by 16.7–28.2% ($P < 0.05$). The fruit wood biochar treatment demonstrated a significant removal of total Pb; however, as the dosage increased, pig manure biochar exhibited a superior removal effect. Additionally, the pig manure biochar-*M. sativa* system showed a significant removal effect on available Pb. Under the *L. perenne* treatment, the total Pb concentration in the soil of the biochar-plant system significantly decreased by 16.6–23.9% ($P < 0.05$) compared to the biochar-only treatment, with available Pb significantly decreasing by 39.5–62.1% ($P < 0.05$). The removal efficiency of the pig manure biochar-*Lolium perenne* system for both total Pb and available Pb was significantly greater than that of the fruit wood biochar-*Lolium perenne* system. Under the *H. spectabile* treatment, the total Pb concentration in the soil of the biochar-plant system significantly decreased by 14.9–25.2% ($P < 0.05$) compared to the biochar-only treatment, while the available Pb significantly decreased by 57.7–70.1% ($P < 0.05$). The combination of pig manure charcoal and *H. spectabile*, along with biochar, demonstrates the most effective removal of total Pb and available Pb. Under the treatment of *S. nigrum*, the total Pb concentration in the soil of the biochar-plant system significantly decreased by 12.1% to 13.5% ($P < 0.05$) compared to the biochar-only treatment, while the available Pb significantly decreased by 15.2% to 28.8% ($P < 0.05$). The removal efficiency of the pig manure biochar and *S. nigrum* system for both total Pb and available Pb was significantly superior to that of the fruit wood biochar-*S. nigrum* system. Among the four herbaceous plants studied, *H. spectabile* and *L. perenne* exhibited the most available Pb removal from the soil. There was no significant difference in the removal efficiency of available Pb between *S. nigrum* and *M. sativa*. Furthermore, the passivation effect of pig manure biochar on Pb was found to be more effective than that of fruit charcoal.

Effects of a biochar-hyperaccumulator system on soil Hg in a mining area. Figure 4 illustrates

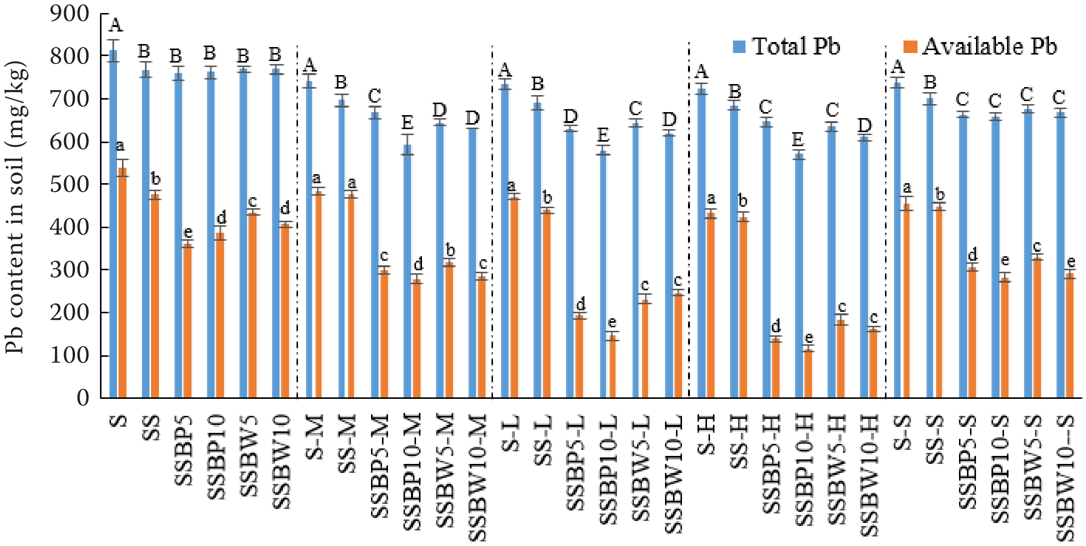

Figure 3. Total and available lead (Pb) content in soil in the biochar-plant system. Data are expressed as means ± standard deviation ($n = 3$). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences in total heavy metal contents among treatments, while different lowercase letters denote significant differences in their available contents

https://doi.org/10.17221/503/2025-PSE

that the addition of farmland soil to S resulted in a significant 31.7% decrease in the total Hg content of SS soil ($P < 0.05$), alongside a 12.4% significant reduction in the available Hg content ($P < 0.05$). Following the application of two types of biochar, the total Hg content in SSBP5, SSBP10, SSBW5, and SSBW10 soils decreased significantly by 9.4% to 14.8% ($P < 0.05$) compared to SS, with the available Hg content also being significantly lower than that in SS, showing a reduction of 32.0% to 45.5% ($P < 0.05$). When used in isolation, pig manure biochar demonstrated superior efficacy in removing both total Hg and available Hg from the soil. The combined approach of soil replacement and biochar addition proved effective for the short-term restoration of available Hg in the soil. Under the *M. sativa* treatment, the total Hg in the biochar-plant system exhibited a significant decrease of 6.6% to 11.3% ($P < 0.05$) compared to the biochar-only treatment, while the available Hg significantly decreased by 8.4% to 25.4% ($P < 0.05$). The pig manure biochar-*M. sativa* system showed a marked ability to remove both total Hg and available Hg. Furthermore, as the dosage of pig manure biochar increased, the efficacy of the pig manure biochar-*M. sativa* system in removing available Hg significantly improved, yielding the best removal effect.

Under the *L. perenne* treatment, the total Hg in the soil of the biochar-plant system significantly decreased by 8.6% to 13.7% compared to the biochar-only treatment ($P < 0.05$), with no significant difference observed in available Hg. The pig manure biochar-*L. perenne* system demonstrated a slightly superior removal effect for both total and available Hg compared to the fruit wood biochar-*Lolium perenne* system. In the case of the *H. spectabile* treatment, the total Hg in the soil of the biochar-plant system was reduced significantly by 13.5% to 20% ($P < 0.05$) compared to the biochar-only treatment, while available Hg was reduced significantly by 30.3% to 44.4% ($P < 0.05$). The pig manure biochar-*H. spectabile* system exhibited a strong removal effect on both total and available Hg. For the *S. nigrum* treatment, total Hg in the soil of the biochar-plant system was significantly reduced by 14.3% to 16.9% ($P < 0.05$) compared to the biochar-only treatment, and available Hg was reduced significantly by 36.8% to 56.0% ($P < 0.05$). Although there was no significant difference in the total Hg removal effect among the different types of biochar and *S. nigrum* systems, the pig manure biochar-*S. nigrum* system showed a significantly greater removal of available Hg than the fruit wood biochar-*S. nigrum* system. Among the four herbaceous plants studied, *S. nigrum* exhibited the most available Hg removal from the soil, followed by *H. spectabile* and *L. perenne*. *M. sativa* demonstrated some removal capacity for both total and available Hg, but its efficacy was inferior to that of the aforementioned plants. The passivation effect

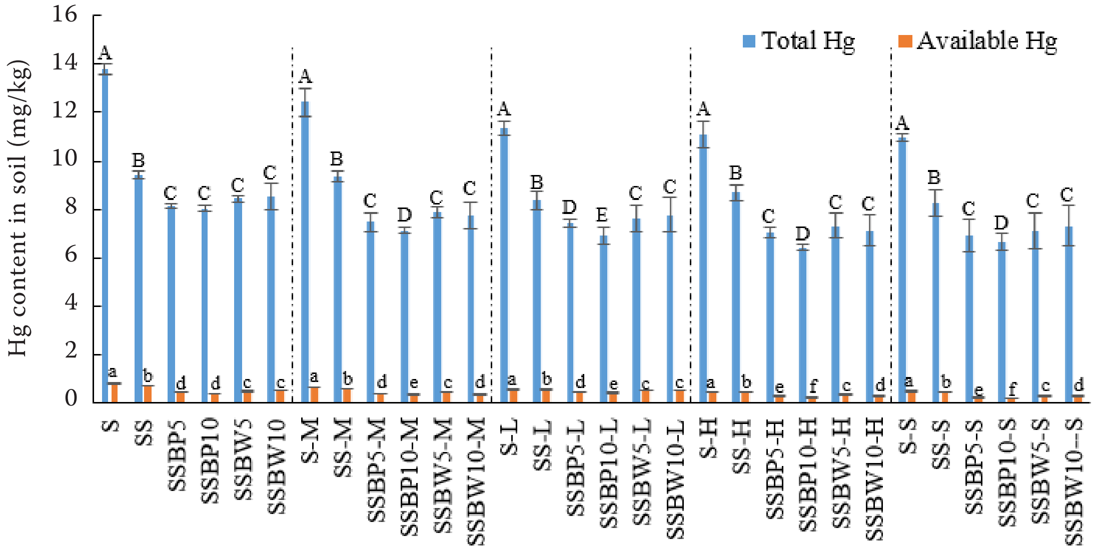

Figure 4. Total and available mercury (Hg) content in soil in the biochar-plant system. Data are expressed as means ± standard deviation ($n = 3$). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences in total heavy metal contents among treatments, while different lowercase letters denote significant differences in their available contents

of pig manure biochar in combination with plants on Hg was found to be equal to or superior to that of fruit wood biochar.

Effects of biochar-hyperaccumulator system on heavy metal accumulation in plants

Effects of biochar-hyperaccumulator system on plant Cd accumulation. The Figure 5 illustrates that the adsorption of Cd in the soil by the four herbaceous plants shows a trend in which the above-ground parts exhibit higher concentrations than the underground parts. Furthermore, the addition of biochar enhances both the adsorption and accumulation of Cd in the soil by these plants. Specifically, the Cd content in the above-ground parts of *M. sativa* ranges from 1.10 to 3.46 mg/kg, while the underground parts contain Cd levels ranging from 0.29 to 0.50 mg/kg. Following the incorporation of biochar, the cumulative Cd content in the above-ground parts of *M. sativa* increased significantly by 166.2% to 214.0% ($P < 0.05$), whereas the underground part experienced a significant increase of 43.6% to 74.4% ($P < 0.05$). In the case of rye grassland, the Cd content in the above-ground parts is measured at 1.63 to 4.06 mg/kg, with underground parts showing Cd levels between 0.43 and 0.72 mg/kg. After biochar application, the cumulative Cd content in the above-ground parts of rye grassland significantly increased by 105.7% to 150.0% ($P < 0.05$), and the underground parts also experienced a similar significant increase of 105.7% to 150.0% ($P < 0.05$). Overall, the cumulative effect on Cd levels has been enhanced significantly by 42.2% to 65.0% ($P < 0.05$).

The Cd content in the above-ground part of *H. spectabile* ranges from 1.84 to 5.05 mg/kg, while the Cd content in the underground part is between 0.48 and 0.71 mg/kg. Following the addition of biochar, the cumulative effect of Cd in the above-ground part of *H. spectabile* increased significantly by 157.4% to 173.6% ($P < 0.05$), and the cumulative effect in the underground part rose significantly by 29.4% to 46.5% ($P < 0.05$). In contrast, the Cd content of the above-ground part of *S. nigrum* is between 1.95 and 6.83 mg/kg, with the underground part containing 0.63 to 0.89 mg/kg. After the addition of biochar, the cumulative effect of Cd in the above-ground part of *S. nigrum* increased significantly by 198.3% to 250.8% ($P < 0.05$), while the cumulative effect in the underground part increased significantly by 15.5% to 40.1% ($P < 0.05$). Pig manure biochar enhances the absorption and accumulation of the heavy metal Cd in the roots of *M. sativa*, *L. perenne*, and *H. spectabile*, demonstrating superior performance compared to fruit wood biochar. However, fruit wood biochar is more effective in promoting the transport of heavy metals in the above-ground parts of *S. nigrum*, as evidenced by the significantly higher Cd content in the above-ground parts of *S. nigrum* treated with

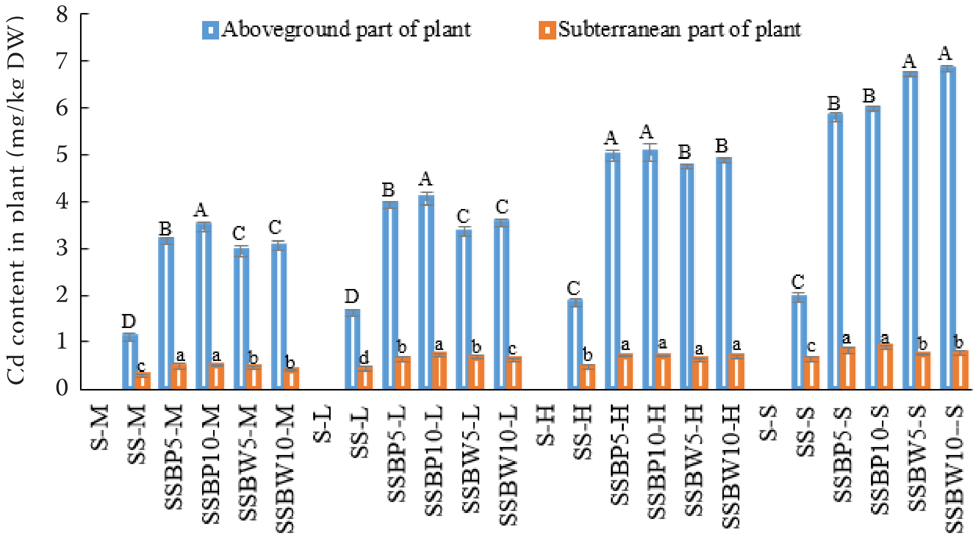

Figure 5. The content of cadmium (Cd) in plants in the biochar-plant system. Data are expressed as means ± standard deviation ($n = 3$). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences in the aboveground parts of plants among treatments, while different lowercase letters denote significant differences in the belowground parts of plants. DW – dry weight

fruit wood biochar compared to those treated with pig manure biochar. The cumulative effect of the four plants on the Cd is ranked as follows: *S. nigrum* > *H. spectabile* > *L. perenne* > *M. sativa.*

Effects of biochar-hyperaccumulator system on Pb accumulation in plants. Figure 6 illustrates that the four herbaceous plants enrich soil with Pb, with above-ground biomass containing higher Pb levels than underground biomass. Furthermore, the addition of biochar enhances the adsorption and accumulation of Pb in the soil associated with these herbaceous plants. Specifically, the Pb content in the above-ground parts of *M. sativa* ranges from 42.2 to 113.2 mg/kg, while the Pb content in the underground parts ranges from 23.6 to 61.4 mg/kg. Following the addition of biochar, the cumulative Pb accumulation in the above-ground parts of *M. sativa* increased significantly by 45.1% to 168.6% ($P < 0.05$), and the cumulative Pb in the underground parts increased significantly by 40.7% to 160.4% ($P < 0.05$). In the case of *L. perenne*, the Pb content in the above-ground parts ranged from 131.9 to 372.1 mg/kg, whereas the underground parts exhibited Pb levels ranging from 37.7 to 70.7 mg/kg. After the addition of biochar, the cumulative Pb effect in the above-ground parts of *L. perenne* increased significantly by 64.2% to 182.0% ($P < 0.05$), while some cumulative effects on Pb in the underground parts increased significantly by 37.4% to 100.2% ($P < 0.05$).

The Pb content in the above-ground part of *H. spectabile* ranges from 165.3 to 420.3 mg/kg, while the Pb content in the underground part ranges from 47.2 to 113.4 mg/kg. Following the addition of biochar, the cumulative effect of *H. spectabile* on Pb in the above-ground part increased significantly by 118.2% to 154.2% ($P < 0.05$), and the cumulative effect in the underground parts increased significantly by 81.3% to 140.4% ($P < 0.05$). In *S. nigrum*, the Pb content in the above-ground part is between 33.5 and 95.8 mg/kg, and the underground part contains 19.2 to 57.5 mg/kg of Pb. After the addition of biochar, the cumulative effect on Pb in the above-ground part of *S. nigrum* increased significantly by 14.1% to 185.6% ($P < 0.05$), while some cumulative effects on Pb increased significantly by 49.6% to 199.0% ($P < 0.05$). Fruit wood biochar enhances the absorption and accumulation of the heavy metal Pb in the roots of *M. sativa*, *L. perenne*, *H. spectabile*, and *S. nigrum*, demonstrating superior performance compared to pig manure biochar. The cumulative effects of the four plants on heavy metal Pb are ranked as follows: *H. spectabile* > *L. perenne* > *M. sativa* > *S. nigrum*.

Effects of biochar-hyperaccumulator system on plant Hg accumulation. The Figure 7 illustrates that the enrichment of Hg in the soil by the four herbaceous plants indicates a trend where the above-ground biomass exhibits higher Hg concentrations than the below-ground biomass. Furthermore, the addition

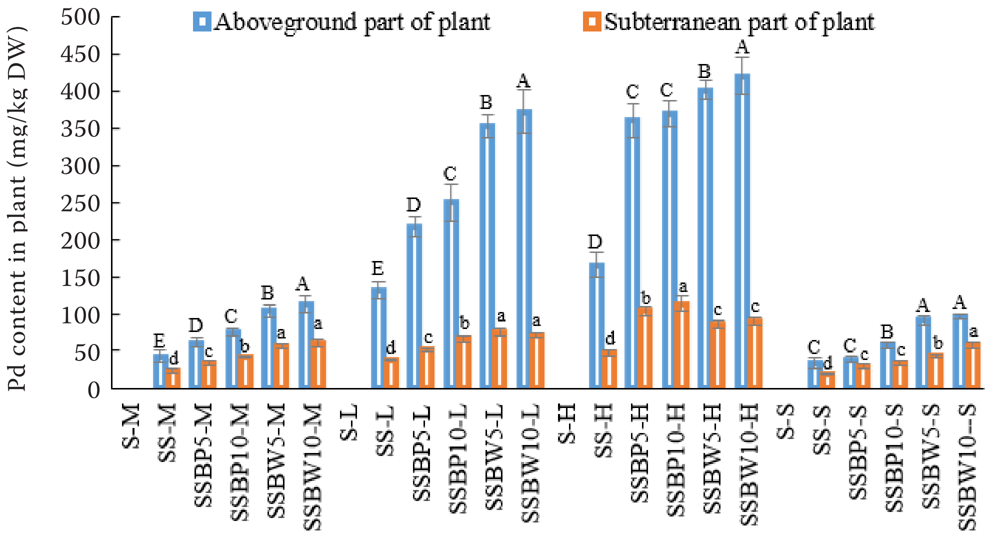

Figure 6. The content of lead (Pb) in plants in biochar-plant system. Data are expressed as means ± standard deviation ($n = 3$). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences in the aboveground parts of plants among treatments, while different lowercase letters denote significant differences in the belowground parts of plants. DW – dry weight

of biochar enhances the adsorption and accumulation of Hg in the soil associated with these plants. Specifically, the Hg content in the above-ground parts of *M. sativa* ranges from 0.056 to 0.123 mg/kg, while the underground parts contain Hg levels between 0.009 and 0.016 mg/kg. With the incorporation of biochar, the cumulative effect of Hg in the above-ground parts of *M. sativa* increased significantly by 96.2% to 121.2% ($P < 0.05$), whereas the underground parts experienced a significant increase of 28.6% to 75.4% ($P < 0.05$). For *L. perenne*, the Hg content in the above-ground parts ranges from 0.068 to 0.153 mg/kg, and the underground parts range from 0.014 to 0.032 mg/kg. Following the addition of biochar, the cumulative effect of Hg in the above-ground parts of *L. perenne* increased significantly by 69.1% to 123.5% ($P < 0.05$), with the underground parts showing a similar significant increase of 69.1% to 123.5% ($P < 0.05$). Overall, the cumulative effect on Hg increased significantly by 59.2% to 131.8% ($P < 0.05$).

The Hg content in the above-ground parts of *H. spectabile* ranges from 0.093 to 0.184 mg/kg, while the Hg content in the underground parts ranges from 0.012 to 0.030 mg/kg. Following the addition of biochar, the cumulative effect of Hg on the above-ground parts of *H. spectabile* increased significantly by 33.3% to 97.4% ($P < 0.05$), and the cumulative effect on the underground parts increased significantly by 100.6% to 157.5% ($P < 0.05$). In contrast, the Hg content in the above-ground parts of *S. nigrum* is between 0.106 and 0.192 mg/kg, and the underground parts contain 0.023 to 0.030 mg/kg. After the addition of biochar, the cumulative effect of Hg on the above-ground parts of *S. nigrum* increased significantly by 56.5% to 81.4% ($P < 0.05$), with a corresponding increase in the underground parts also ranging from 56.5% to 81.4%. Overall, the cumulative effect on Hg increased significantly by 154.1% to 222.1% ($P < 0.05$). Pig manure biochar is shown to enhance the absorption and accumulation of the heavy metal Hg in the above-ground parts of *M. sativa*, *L. perenne*, *H. spectabile*, and *S. nigrum*, demonstrating superior effectiveness compared to fruit wood biochar. The cumulative effect of these four plants on heavy metal Hg follows the order: *S. nigrum* > *H. spectabile* > *L. perenne* > *M. sativa*.

Effect of biochar-hyperaccumulator system on soil physicochemical properties

Effects of biochar-hyperaccumulator system on soil nutrient content. As shown in Figure 8A, the slag pH measured 7.35, indicating a neutral condition. After soil incorporation, the pH of CK-SS increased significantly to 7.64 ($P < 0.05$), approaching the lower threshold of weakly alkaline soil. Biochar addition significantly raised the soil pH to a range of 8.22 to 8.29 ($P < 0.05$), classifying it as weakly

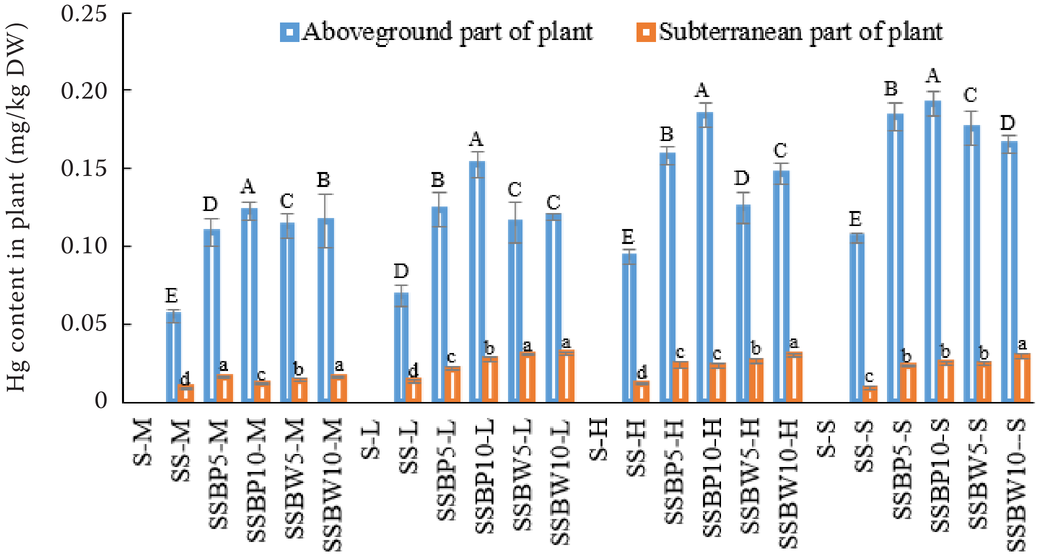

Figure 7. The content of mercury (Hg) in plants in biochar-plant system. Data are expressed as means ± standard deviation ($n = 3$). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences in the aboveground parts of plants among treatments, while different lowercase letters denote significant differences in the belowground parts of plants. DW – dry weight

alkaline. Plant type had no significant effect on soil pH, indicating that biochar application was the main factor regulating pH changes.

As shown in Figure 8B, the slag had a low organic carbon content of only 3.64 g/kg. After mixing with soil, the organic carbon content reaches 6.40 g/kg, which is classified as a low-organic-carbon level. Biochar application significantly increased soil organic carbon, with pig manure biochar demonstrating superior efficacy compared to fruit wood biochar. In the absence of plants, pig manure biochar increased significantly soil organic carbon by 5.19- to 6.26-fold ($P < 0.05$), while fruit wood biochar resulted in 2.78- to 3.12-fold significant increases. After plant cultivation, soil organic carbon decreased significantly, ranging from 13.11 to 33.31 g/kg. Herbaceous plants, when grown in nutrient-poor soils, exhibit a heightened reliance on soil organic carbon, leading to a significant depletion of organic carbon content in the soil. Among the species, *L. perenne* treatments retained the highest residual organic carbon, from 9.09 to 33.31 g/kg, whereas *S. nigrum* showed the lowest, ranging from 8.37 to 20.38 g/kg.

As shown in Figure 8C, the available potassium content was 108 mg/kg in slag and 142 mg/kg in soil after incorporation. Biochar application significantly increased available potassium, with pig manure biochar resulting in a greater increase than fruit wood biochar. In unplanted soil, pig manure biochar increased available potassium by 4.37 to 4.66 times ($P < 0.05$), while fruit wood biochar increased it by 3.22 to 3.62 times ($P < 0.05$). After planting, available potassium in pig manure biochar-treated soil decreased significantly by 18.52% to 27.75% ($P < 0.05$), whereas the decrease under fruit wood biochar was not significant, with values ranging from 439 mg/kg to 503 mg/kg. Research indicates that wood biochar possesses a low cation-exchange capacity, high stability, and a durable carbon sequestration ability, which can enhance the efficiency of soil fertility utilisation after ageing treatment.

As shown in Figure 8C, the available phosphorus content was 7.1 mg/kg in slag and increased significantly to 11.80 mg/kg ($P < 0.05$) after soil incorporation. Biochar application significantly enhanced available phosphorus, with pig manure biochar yielding greater increases than fruit wood biochar. In unplanted soil, pig manure biochar significantly raised available phosphorus by 3.41 to 4.04 times ($P < 0.05$), while fruit wood biochar resulted in 2.09 to 2.35 times significant increases. After planting, available phosphorus decreased significantly under pig manure biochar treatment, with reduction rates ranging from 19.6% to 45.51% ($P < 0.05$), particularly in soils planted with *H. spectabile* and *S. nigrum*, where reductions reached 40.18% to 45.51% ($P < 0.05$). Under fruit wood biochar, the decrease varied from 0.41% to 32.49% ($P < 0.05$), with *S. nigrum*, *H. spectabile*, and *M. sativa* showing high phosphorus utilisation efficiency.

As shown in Figure 8B, the total nitrogen content was 0.69 g/kg in slag and significantly increased to 0.77 g/kg ($P < 0.05$) after soil incorporation. Biochar application significantly enhanced total nitrogen, with pig manure biochar producing greater increases than fruit wood biochar. In unplanted soil, pig manure biochar significantly raised total nitrogen by 2.80 to 3.21 times ($P < 0.05$), while fruit wood biochar resulted in 1.60 to 2.15 times significant increases. After planting, total nitrogen under pig manure biochar decreased significantly by 27.10% to 48.63% ($P < 0.05$), with the highest reduction observed under *S. nigrum* at 44.53% to 48.63%. In contrast, the significant decrease under fruit wood biochar ranged from 1.43% to 35.20%, with *H. spectabile* and *S. nigrum* showing high nitrogen utilisation efficiency.

The nutrients supplied by this biochar provided better nutritional support for plant growth. Studies indicate that wood biochar has low cation exchange capacity, strong stability, and carbon sequestration capacity, which can improve the utilisation efficiency of soil fertility after ageing treatment (Rahi et al. 2022, Xu et al. 2022, Savitri et al. 2023). The nutrient variation trends in soil differ across plant types, and nutrient utilisation rates also vary, primarily depending on plant biological characteristics. The root structures of the four studied plants exhibit significant differences, resulting in varying nutrient requirements among the species.

Effects of biochar-hyperaccumulator system on soil enzyme activity. As shown in Figure 9, initial enzyme activities in slag were extremely low: dehydrogenase at 12.6 μg/g/24 h, phosphatase at 75.4 μg/g/24 h, catalase at 1.2 mL/g/20 min, and urease at 62.6 μg/g/24 h. Soil incorporation significantly increased these activities by 2.89, 2.61, 2.30, and 2.92 times, respectively ($P < 0.05$). Biochar application further enhanced all enzyme activities, with pig manure biochar showing superior effects – increasing significantly dehydrogenase 2.05–2.15 times, phosphatase 1.43–1.69 times, catalase 1.48–1.59 times, and urease 1.77–1.84 times ($P < 0.05$). Fruit wood

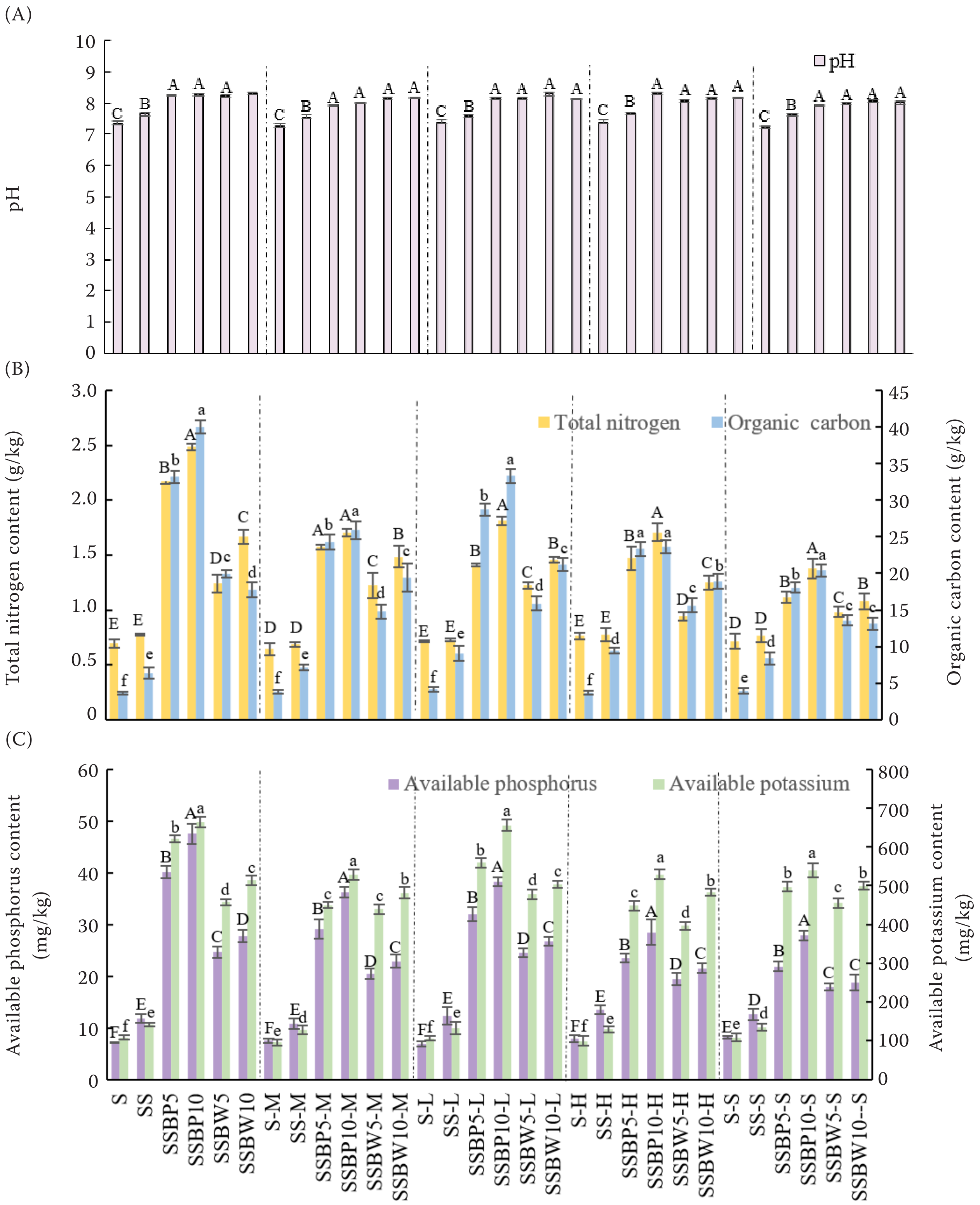

Figure 8. Soil physicochemical properties in biochar-plant system; (A) pH; (B) total nitrogen and organic carbon content, and (C) available phosphorus and available potassium. Data are expressed as means ± standard deviation ($n = 3$). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences among treatments for the indicator on the left axis, while different lowercase letters denote significant differences for the indicator on the right axis

biochar resulted in significantly increased levels of 1.49–1.76 times for dehydrogenase, 1.22–1.43 times for phosphatase, 1.13–1.32 times for catalase, and 1.32–1.42 times for urease ($P < 0.05$). The combined application of plants and biochar further enhanced all four enzyme activities.

Under biochar amendment, the enhancement of soil enzyme activities varied significantly among plant species. *S. nigrum* consistently showed the highest promoting effect, increasing significantly dehydrogenase by 36.67% to 45.83%, phosphatase by 58.67% to 64.94%, catalase by 52.45% to 59.32%, and urease by 59.08% to 66.92% ($P < 0.05$). *H. spectabile* ranked second, significantly enhancing dehydrogenase by 33.65% to 42.68%, phosphatase by 46.56% to 50.81%, catalase by 44.67% to 53.17%, and urease by 53.24% to 58.74% ($P < 0.05$). *L. perenne* and *M. sativa* followed, with *L. perenne* significantly increasing dehydrogenase by 17.37% to 25.00%, phosphatase by 48.92% to 54.12%, catalase by 40.57% to 48.39%, and urease by 41.33% to 57.35% ($P < 0.05$), while *M. sativa* showed the moderate but significant enhancements of 7.49% to 19.95% for dehydrogenase, 25.64% to 33.24% for phosphatase, 25.58% to 36.62% for catalase, and 37.06% to 43.66% for urease ($P < 0.05$).

Organic acids, enzymes, and other substances secreted by plant roots can enhance nutrient release and absorption. The enzyme activity in the soil was initially very low. However, the application of biochar significantly improved this activity. Furthermore, the

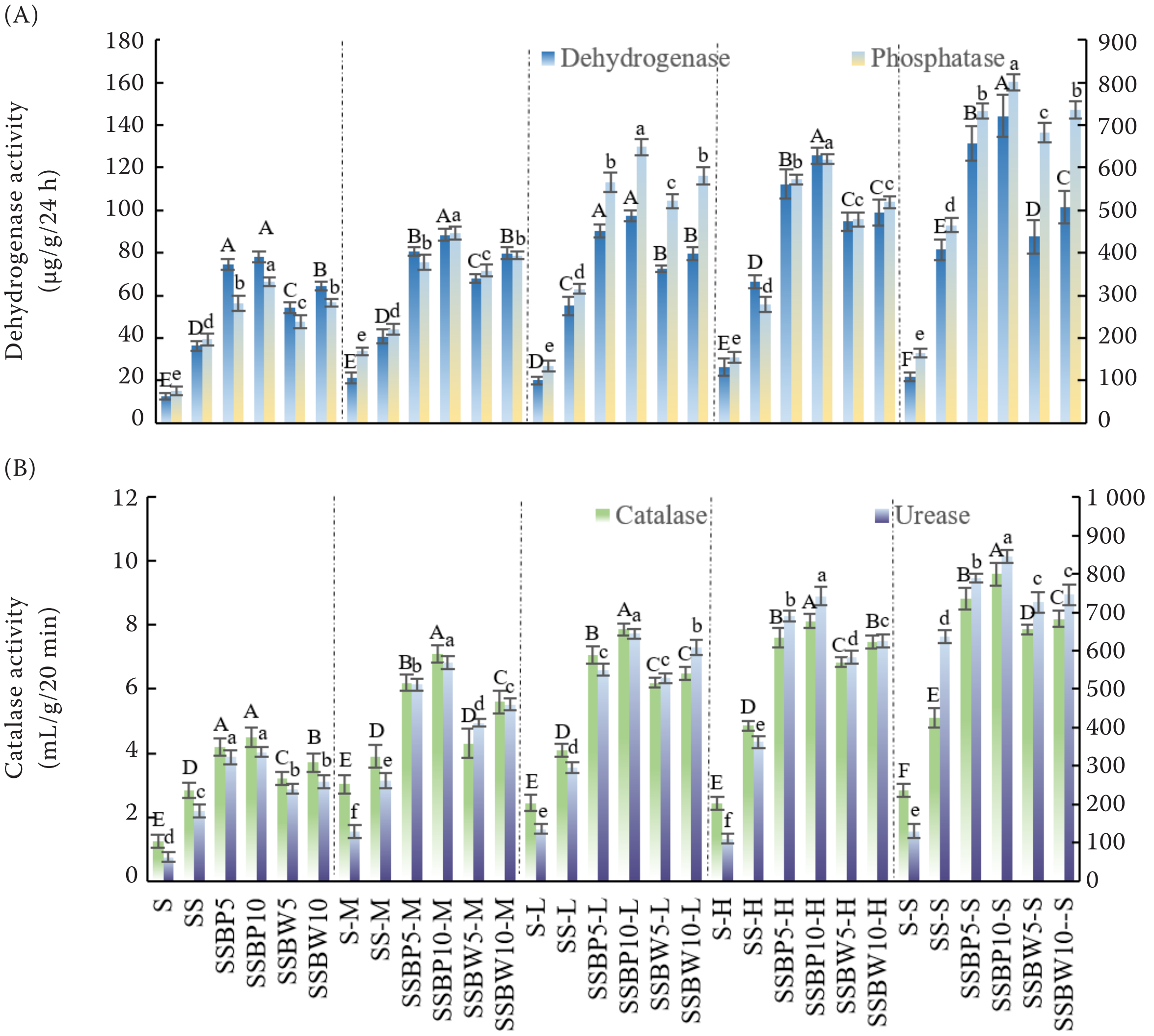

Figure 9. Enzyme activity in soil of biochar-plant system. (A) dehydrogenase and phosphatase, and (B) catalase and urease. Data are expressed as means ± standard deviation ($n = 3$). Statistical significance was determined using two-way ANOVA followed by Fisher's least significant difference (*LSD*) test ($P < 0.05$). Different uppercase letters indicate significant differences among treatments for the indicator on the left axis, while different lowercase letters denote significant differences for the indicator on the right axis

combined effect of biochar and plants continued to promote the enhancement of enzyme activity in the soil. Notably, the combination of pig manure biochar with *S. nigrum* yielded the most effective results in promoting enzyme activity. Overall, the application of biochar not only provides essential nutrients for plant growth but also promotes increased plant height, biomass accumulation, and enhances the potential for heavy metal migration.

Correlation of the biochar-hyperaccumulator system on soil chemistry and heavy metal migration behaviour

Figure 10 presents redundancy analysis (RDA) of the relationships among heavy metals in soil and plants, soil properties, and plant characteristics under different biochar-plant systems. Strong correlations were observed between total and available heavy metals in soil, indicating that the reduction of heavy metals under combined biochar and plant treatment was primarily driven by decreased availability. The combined application effectively reduced both total and available heavy metal concentrations. Significant negative correlations were observed between heavy metal concentrations and soil nutrients and plant traits, confirming that the biochar-plant system simultaneously enhanced soil fertility while mitigating heavy metal concentrations. This aligns with previous studies showing that organic carbon and phosphorus can immobilise heavy metals through precipitation and complexation (Alhar et al. 2021, Xu et al. 2022, Zhao et al. 2024). Improved nutrient conditions enhanced plant stress resistance and growth under metal stress, further influencing metal distribution in the soil-plant system (Jain et al. 2020, Ghosh and Maiti 2021, Gao et al. 2022).

Positive correlations between plant metal uptake and soil nutrients/plant traits indicated synergistic effects, with biochar-mediated nutrient supply promoting root development and biomass, thereby enhancing metal accumulation. The more active root activities of plants lead to the secretion of greater amounts of organic acids and enzymes, further facilitating the mobilisation and uptake of metals by hyperaccumulators (Zhu et al. 2022, Wang et al. 2025). Positive correlations among soil nutrients reflected the beneficial role of biochar amendment. In summary, the biochar-plant system significantly improved soil quality while reducing heavy metal availability, demonstrating high feasibility for remediating contaminated mining areas.

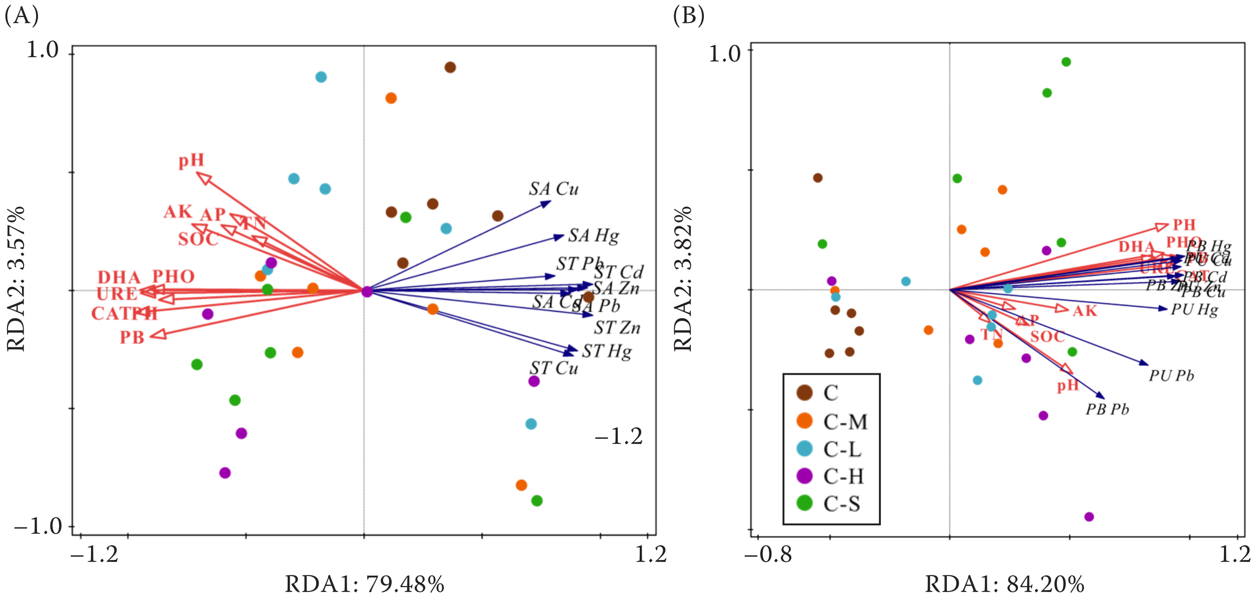

Figure 10. (A) Redundancy analysis (RDA) of the correlation among the total amount of heavy metals, the available content and the physicochemical properties of soil and the physiological characteristics of plants, and (B) the redundancy analysis of the correlation between heavy metals in plants and the physicochemical properties of soil and the physiological characteristics of plants. C – treatment with only biochar applied; C-M – combined treatment of biochar with *Medicago sativa*; C-L – treatment of biochar with *Lolium perenne*; C-H – treatment of biochar with *Hylotelephium spectabile*; C-S – treatment of biochar with *Solanum nigrum*

https://doi.org/10.17221/503/2025-PSE

DISCUSSION

Removal mechanism of heavy metals from slag soil by biochar. Pure slag is highly toxic due to the presence of heavy metals, which can inhibit the growth and development of soil organisms. Soil replacement and biochar addition can significantly reduce the concentrations of available Pb, Cd, and Hg. Notably, the total amounts of Hg and Cd decreased significantly following biochar application. The passivation effect of pig manure biochar on the bioavailable forms of heavy metals, specifically Pb and Hg, was found to be superior to that of fruit wood biochar. Biochar primarily immobilises heavy metals on its surface through mechanisms such as adsorption, ion exchange, complexation, and precipitation. In addition to this direct effect, cations and ionisable protons, such as Na^+, K^+, Ca^{2+}, and Mg^{2+}, present on the surface of biochar can be readily replaced by heavy metal ions through ion exchange (Wang et al. 2022a, Emamverdian et al. 2024). Generally, the higher the cation exchange capacity (CEC) of biochar, the more pronounced its exchangeability effect. Studies indicate that livestock and poultry manure biochar exhibits a higher CEC, and ion exchange plays a crucial role in the immobilisation of heavy metals. Furthermore, biochar contains inorganic minerals, including carbonates and phosphates (Xu et al. 2022). Livestock and poultry manure biochar is characterised by a high pH and ash content. The fixation mechanism for heavy metals also involves mineral precipitation, whereby hydroxides and hydroxyl radicals released by various inorganic minerals interact with heavy metal ions (Ayaz et al. 2022). Anions such as carbonate and phosphate can form precipitates with these heavy metals (Sha et al. 2023). Given that pig manure biochar contains a higher concentration of inorganic minerals compared to fruit wood biochar, its superior fixation and enrichment effects on heavy metals can be attributed primarily to ion exchange and precipitation, which aligns with the findings of this study.

Effects of biochar-hyperaccumulator system on the removal of heavy metals from slag soil. When grown in isolation, all four plant species demonstrated significant capacity to remove heavy metals from the soil. The combination of biochar with a hyperaccumulator plant system exhibited superior heavy metal removal efficacy compared to either biochar alone or the hyperaccumulators independently. The order of Cd removal efficiency among the four herbaceous plants was as follows: *S. nigrum* > *H. spectabile* > *M. sativa* > *L. perenne*. This trend was also reflected in the Cd enrichment coefficients of the herbaceous plants. The application of biochar markedly enhanced plants' ability to accumulate Cd, with the combination of plants and pig manure biochar showing a better Cd removal efficiency than fruit wood biochar. In terms of Pb removal, the efficacy of the four herbaceous plants ranked as follows: *H. spectabile* > *L. perenne*. Notably, *M. sativa* and *S. nigrum* exhibited no significant difference in Pb removal efficiency and were less effective than the aforementioned species. This ranking was consistent with the Pb enrichment coefficients of the herbaceous plants. Furthermore, the application of biochar significantly improved the plants' capacity to accumulate Pb, with the enrichment effect observed in plants treated with fruit wood biochar being superior to that of those treated with pig manure biochar. In summary, the phytoremediation technology applied to complex heavy metal-contaminated mining areas has demonstrated that *H. spectabile* exhibits excellent enrichment performance. The application of biochar enhances hyperaccumulators' ability to take up heavy metals. Generally, pig manure biochar, when combined with hyperaccumulators, shows a more effective removal of heavy metals compared to fruit wood biochar. Research indicates that the solubility of minerals in biochar ash and the precipitation-dissolution dynamics of heavy metals reach a state of equilibrium (Yang et al. 2021, Gao et al. 2022). Notably, pig manure biochar contains higher levels of inorganic minerals than fruit wood biochar, which aligns with the findings of this study that highlight the role of pig manure biochar in promoting the stabilisation of heavy metals (Ayaz et al. 2022). This biochar effectively anchors heavy metals within the plant root system, allowing for their accumulation and subsequent transport into the plant body. The results of this research are consistent.

Mechanism of removal of heavy metals from slag soil by biochar-hyperaccumulator system. When biochar is applied to soil as a passivating agent, it reduces the bioavailability of heavy metals. This phenomenon aligns with previous research findings (Li et al. 2022, Liu et al. 2024a). The application of biochar introduces organic carbon to the originally barren slag soil. Given biochar's fine texture, its use promotes the formation of soil aggregates and enhances the soil's capacity to adsorb and passivate heavy metals. Research has demonstrated a negative correlation between the content of organic matter and the bioavailability of heavy metals in the soil (Jain et al. 2017, Alhar et al. 2021, Ai et al. 2023). Furthermore, the combination of biochar application with the cultivation of hyperaccumulators further decreases the bioavailability of heavy metals in the soil. Notably, the application of biochar significantly enhances heavy metal accumulation in hyperaccumulators.

The characteristics of the tested soil indicate that the slag soil exhibits a coarser texture and a high availability of heavy metals. This may explain why hyperaccumulators are more effective at accumulating heavy metals. The four herbaceous plants chosen for this study are all wild species known for their robust stress resistance. They possess strong vitality and adaptability, allowing them to thrive in harsh soil environments. These traits align with the fundamental requirements of phytoremediation technology for soil pollution remediation, specifically, rapid growth and substantial biomass production. Among the four plants studied, *H. spectabile* demonstrated the greatest Pb removal capacity. Previous research has indicated that *H. spectabile* exhibits excellent remediation capabilities for Zn, Pb, and Cd, whether addressing single heavy metals or composite mixtures, findings consistent with this study (Guo et al. 2025). Furthermore, *H. spectabile* also effectively removes Cd and Hg. This plant maintains heavy metal absorption by reducing root transcription levels and the expression of root transporters, while simultaneously promoting the synthesis of proteins related to photosynthesis, antioxidant processes, and metabolic functions in its aboveground tissues (Guo et al. 2022). It is also plausible that significant amounts of heavy metals accumulate in the aboveground parts, and that their interaction with these proteins enhances *H. spectabile's* capacity to transport them. Comparing the four plants, *S. nigrum* exhibits the most effective removal of Cd and Hg. Research indicates that the phytoremediation capability of *S. nigrum* in soils contaminated with cadmium and complex heavy metals, such as Pb, Cu, and Zn, remains unaffected. In fact, the height, fresh weight, and dry weight of *S. nigrum* have increased to a certain extent, and the biomass accumulation coefficient of *S. nigrum* was found to be higher than that observed under single Cd treatment (Yu et al. 2015). *S. nigrum* induces the accumulation of proline (Pro) in soil with higher concentrations of heavy metals. Proline enhances the activity of superoxide dismutase (SOD) and catalase (CAT), thereby reducing reactive oxygen species (ROS) levels under Cd stress. This process protects the integrity of the cell membrane, ultimately improving *S. nigrum*'s tolerance to heavy metal stress and promoting heavy metal accumulation.

Studies have demonstrated that in heavy metal-contaminated soil, *M. sativa* exhibits a significant increase in heavy metal content as the concentration of heavy metals in the soil rises. Heavy metal pollution results in elevated activities of peroxidase and glutathione-S-transferase (GST) in the plant, alongside a notable accumulation of malondialdehyde (MDA). This response plays a crucial role in the detoxification process of *M. sativa* (Hantsi et al. 2025). While the heavy metal enrichment capacity of *M. sativa* is not as pronounced as that of *H. spectabile* and *S. nigrum*, it still contributes to the removal of heavy metals. *L. perenne*, a gramineous monocotyledonous plant characterised by its robust regenerative ability and well-developed root system, has been shown to promote its own growth under heavy metal stress. Notably, even under high Zn concentrations, the dry weight of the above-ground portion of *L. perenne* remains greater than that observed in the absence of Zn treatment. Furthermore, *L. perenne* protects its cell membranes from heavy metal-induced damage primarily by modulating the activity of its antioxidant enzymes, such as superoxide dismutase and peroxidase (POD) (Zhang et al. 2023). In this study, *L. perenne* also demonstrated efficacy in the removal of heavy metals.

Effects of biochar-hyperaccumulator system on soil and phytochemical properties. The slag is poor in various nutrients. The application of two types of biochar significantly increased the soil contents of organic carbon, available potassium, available phosphorus, and total nitrogen. Among these, pig manure biochar demonstrated a superior capacity to enhance the four nutrient types compared to fruit wood biochar. Following crop planting, the soil nutrient content decreased significantly under pig manure biochar treatment. However, the nutrients supplied by this biochar provided better nutritional support for plant growth. Conversely, under the treatment of fruit wood biochar, the nutrient utilisation rate of plants was lower than that observed with pig manure biochar. Studies indicate that wood biochar has low cation exchange capacity, strong stability, and carbon sequestration capacity, which can improve the efficiency of soil fertility utilisation after ageing treatment (Rahi et al. 2022, Xu et al. 2022, Savitri et al. 2023). The nutrient variation trends in soil differ across plant types, and plant nutrient utilisation rates also vary, primarily depending on plant biological characteristics. The root structures of the four studied plants exhibit significant differences, leading to varying nutrient requirements among different species. Additionally, organic acids, enzymes, and other substances secreted by plant roots can enhance the release and absorption of nutrients. The enzyme activity in the soil was initially very low. However, the application of biochar significantly improved this activity. Furthermore, the combined effect of biochar and plants continued to promote the enhancement of enzyme activity in the soil. Notably, the combination of pig manure biochar with *S. nigrum* yielded the most effective results in promoting enzyme activity. Overall, the application of biochar not only provides essential nutrients for plant growth but also promotes increased plant height, biomass accumulation, and enhances the potential for heavy metal migration.

Practical application suggestions for composite technology. Based on the results of this study, it is recommended to prioritise the use of *S. nigrum* in areas contaminated with Cd and Hg, while *H. spectabile* should be the preferred choice for Pb-contaminated regions. Building on the selection of these plants, pig manure biochar can be further prioritised as a complementary measure for heavy-metal remediation. If pig manure biochar is not readily available, fruitwood charcoal also serves as a good alternative option. Despite the differences in the treatment effects of various types of biochar and hyperaccumulator plants on different heavy metals, biochar and hyperaccumulator plants exhibit a synergistic remediation effect on multiple heavy metals. Therefore, as long as the mining area contains the same type of heavy metal pollution as in this study, and there are no other adverse factors that affect the properties of biochar or cause other toxic effects on hyperaccumulator plants, the remediation measures explored in this study using the combination of biochar and hyperaccumulator plants for heavy metals are highly feasible. The harvested materials of hyperaccumulator plants should be classified as hazardous waste, which can be managed through incineration followed by solidification and landfilling, or by exploring high-temperature pyrolysis to convert them into stable biochar. This approach effectively immobilises heavy metals within the carbon matrix, significantly reducing their leachability and toxicity. The resulting biochar, once it meets safety standards, can be considered for use as engineering fill or other enclosed applications, thereby achieving the ultimate sequestration of heavy metals and technically severing the chain of secondary pollution.

Feasibility analysis of composite technology promotion. China produces approximately 3.8 billion tons of livestock and poultry manure annually, with pig manure accounting for 47% of this total. The total amount of orchard waste reaches 142 million tons, with an average annual growth of 843 000 tons. The raw materials for the two types of biochar are abundant and easily accessible, both of which are waste products with stable sources. The research on their resource utilisation has always been a challenge in the industry. The results of this study provide a green economic solution for sites contaminated with heavy metals, while also offering new ideas for the utilisation of waste resources.

The combined application of biochar and hyperaccumulator plants is a risk-free measure that improves soil quality and restores ecological environments in areas severely contaminated with heavy metals. It serves as an ecological safety measure conducive to regional governance. The raw materials for the two types of biochar, which are wastes requiring treatment, incur only minimal acquisition and transportation costs. The primary energy consumption occurs during the pyrolysis and processing stages. Pig manure and fruit tree branches not only serve as raw materials for biochar but also contain considerable energy value. In the pyrolysis process, the combustible gas generated from pig manure can be reused to provide the thermal energy required by the system, achieving partial energy self-sufficiency. Due to the high lignin content and high calorific value of fruit wood, the heat released during carbonisation can sustain the reaction, demonstrating significant energy balance potential. The preparation pathways of these two types of biochar exemplify a synergistic enhancement from "waste" to "process energy" and "end product", providing a key pathway to reduce processing energy consumption and enhance overall economic viability. This method is more cost-effective than chemical amendments or soil leaching for removing heavy metals.

The primary application scenario for biochar technology, used in conjunction with hyperaccumulator plants for heavy metal remediation, is in areas contaminated with heavy metals, such as industrial sites and mining areas. These regions are often the result of mining development, production, and processing activities and may be characterised by natural conditions that negatively affect plant establishment and growth, such as drought, nutrient deficiencies, and unsuitable temperatures. The promising application prospects of the biochar and hyperaccumulator plant combined remediation technology in these areas stem from several advantages: biochar can immobilise the migration of heavy metals while enhancing soil organic carbon, thereby improving soil quality. Hyperaccumulator plants themselves possess strong stress resistance, and with the dual support of biochar in reducing heavy metal toxicity and providing nutrients, they can grow better and further accumulate heavy metals from contaminated soils. In this combined remediation technology, biochar helps alleviate toxicity around plant roots, targets heavy metals to reduce their mobility within a specific range, and provides nutrients to promote the growth of hyperaccumulator plants, thereby creating a favourable microenvironment for them. Hyperaccumulator plants have a distinct advantage in the early stages of establishment in contaminated sites, as they have a wide range of suitable survival conditions and strong competitiveness for nutrients and moisture. As they grow, hyperaccumulator plants can accumulate heavy metals in their tissues and produce root exudates that increase the complexity and stability of the rhizosphere microbial network, thereby suppressing harmful competition.

The application of biochar in this study is a core improvement step aimed at addressing the harsh conditions that negatively impact the growth of hyperaccumulating plants, such as soil infertility and coarse texture in mining areas. The addition of biochar can rapidly create a viable "rhizosphere microenvironment" for plants. Technical measures involving the combination of biochar and hyperaccumulating plants have been validated through pot experiments, demonstrating their excellent effects. However, there is still a lack of application data verification from actual mining sites. We will continue to expedite coordination with mining areas for planning experimental sites, and the next step will be to conduct long-term monitoring experiments in the mining areas to further evaluate the long-term effectiveness and sustainability of this combined technology.

REFERENCES

Ai Y., Wang Y., Song L., Hong W., Zhang Z., Li X., Zhou S., Zhou J. (2023): Effects of biochar on the physiology and heavy metal enrichment of *Vetiveria zizanioides* in contaminated soil in mining areas. Journal of Hazardous Materials, 448: 130965.

Alhar M., Thompson D., Oliver I. (2021): Mine spoil remediation *via* biochar addition to immobilise potentially toxic elements and promote plant growth for phytostabilisation. Journal of Environmental Management, 277: 111500.

Ayaz M., Stulpinaite U., Feiziene D., Tilvikiene V., Akthar K., Baltenaite-Gedien E., Striugas N., Rehmani U., Alam S., Iqbal R., Toleikiene M., Doyeni M. (2022): Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil. Soil Use and Management, 38: 1307–1321.

Chen X., Lin Q., Xiao H., Muhammad R. (2023a): Manganese-modified biochar promotes Cd accumulation in *Sedum alfredii* in an intercropping system. Environmental Pollution, 317: 120525.

Chen X., Wong C., Zhang H. (2023b): Analysis and pollution evaluation of heavy metal content in soil of the Yellow River Wetland Reserve in Henan. PEERJ, 11: e16454.

Eid E., Shaltout K. (2016): Bioaccumulation and translocation of heavy metals by nine native plant species grown at a sewage sludge dump site. International Journal of Phytoremediation, 18: 1075–1085.

Emamverdian A., Ghorbani A., Pehlivan N., Li Y., Zargar M., Liu G. (2024): Bamboo biochar helps minimize *Brassica* phytotoxicity driven by toxic metals in naturally polluted soils of four mine zones. Environmental Technology and Innovation, 36: 103753.

Fu Y., Jia M., Wang F., Wang Z., Mei Z., Bian Y., Jiang X., Virta M., Tiedje J. (2021): Strategy for mitigating antibiotic resistance by biochar and hyperaccumulators in cadmium and oxytetracycline co-contaminated soil. Environmental Science and Technology, 55: 16369–16378.

Gao Y., Wu P., Jeyakumar P., Bolan N., Wang H., Gao B., Wang S., Wang B. (2022): Biochar as a potential strategy for remediation of contaminated mining soils: Mechanisms, applications, and future perspectives. Journal of Environmental Management, 313: 114973.

Ghosh D., Maiti S. (2021): Biochar-assisted eco-restoration of coal mine degraded land to meet United Nation Sustainable Development Goals. Land Degradation and Development, 32: 4494–4508.

Guo X., Zhang S., Luo J., Pan M., Du Y., Liang Y., Li T. (2022): Integrated glycolysis and pyrolysis process for multiple utilization and cadmium collection of hyperaccumulator *Sedum alfredii*. Journal of Hazardous Materials, 422: 126859.

Guo B., Wei Y., Liu X., Qian T., Guo J., Yang J., Chen T. (2025): Water-soluble carboxymethyl chitosan and rhamnolipids promote the remediation of Cd-contaminated soil by mediating the growth of *Hylotelephium spectabile* and regulating the rhizospheric ecological environment. Journal of Hazardous Materials, 486: 137040.

Hantsi J., Melato F., Tembu V. (2025): Extraction potential of *Trifolium repens* and *Medicago sativa* for metals in landfill soil: their metabolomic responses. Journal of Environmental Management, 373: 123867.

Huang S., Huang Z., Chen Z., Wang J., Evrendilek F., Liu J., He Y., Ninomiya Y., Xie W., Zhuang G., Sun S. (2024): Simultaneous optimizations of heavy metal immobilizations, products, temperature, and atmosphere dependency by acid pretreatment-assisted pyrolysis and gasification of hyperaccumulator (*Pteris vittate* L.): biomass. Journal of Cleaner Production, 450: 142004.

Jain S., Khare P., Mishra D., Shanker K., Singh P., Singh R., Das P., Yadav R., Saikia B., Baruah B. (2020): Biochar aided aromatic grass [*Cymbopogon martini* (Roxb.): Wats.] vegetation: A sustainable method for stabilization of highly acidic mine waste. Journal of Hazardous Materials, 390: 121799.

Jain S., Singh A., Khare P., Chanda D., Mishra D., Shanker K., Karak T. (2017): Toxicity assessment of *Bacopa monnieri* L. grown in biochar amended extremely acidic coal mine spoils. Ecological Engineering, 108: 211–219.

Li Q., Liang W., Liu F., Wang G., Wan J., Zhang W., Peng C., Yang J. (2022): Simultaneous immobilization of arsenic, lead and cadmium by magnesium-aluminum modified biochar in mining soil. Journal of Environmental Management, 310: 114792.

Liu J., Qiu R., Wei X., Xiong X., Ren S., Wan Y., Wu H., Yuan W., Wang J., Kang M. (2024a): $MnFe_2O_4$-biochar decreases bioavailable fractions of thallium in highly acidic soils from pyrite mining area. Environmental Research, 241: 117577.

Liu T., Chen Z., Li Z., Fu H., Chen G., Feng T., Chen Z. (2021): Preparation of magnetic hydrochar derived from iron-rich *Phytolacca acinosa* Roxb. for Cd removal. Science of The Total Environment, 769: 145159.

Liu Z., Liu S., Gao L., Li J., Li X., Jing Z., Song W. (2024b): Long-term recovery of compacted reclaimed farmland soil in coal mining subsidence area. Ecological Indicators, 168: 112758.

Mohanty C., Selvaraj C. (2025): Leveraging plant-based remediation technologies against chromite mining toxicity. International Journal of Phytoremediation, 27: 192–205.

Nejad Z., Kim J., Jung M. (2017): Reclamation of arsenic contaminated soils around mining site using solidification/stabilization combined with revegetation. Geosciences Journal, 21: 385–396.

Padhi P., Bora N., Sohtun P., Athparia M., Kumar M., Kataki R., Sarangi P. (2024): Remediation of mine overburden and contaminated water with activated biochar derived from low-value biowaste. Journal of The Taiwan Institute of Chemical Engineers, 159: 105472.

Penido E., Martins G., Mendes T., Melo L., Guimaraes I., Guilherme L. (2019): Combining biochar and sewage sludge for immobilization of heavy metals in mining soils. Ecotoxicology and Environmental Safety, 172: 326–333.

Qin J., Niu A., Liu Y., Lin C. (2021): Arsenic in leafy vegetable plants grown on mine water-contaminated soils: uptake, human health risk and remedial effects of biochar. Journal of Hazardous Materials, 402: 123488.

Rahi A., Younis U., Ahmed N., Ali M., Fahad S., Sultan H., Zarei T., Danish S., Taban S., El Enshasy H., Tamunaidu P., Alotaibi J., Alharbi S., Datta R. (2022): Toxicity of cadmium and nickel in the context of applied activated carbon biochar for improvement in soil fertility. Saudi Journal of Biological Sciences, 29: 743–750.

Savitri S., Reguyal F., Sarmah A. (2023): A feasibility study on production, characterisation and application of empty fruit bunch oil palm biochar for Mn^{2+} removal from aqueous solution. Environmental Pollution, 318: 120879.

Sha H., Li J., Wang L., Nong H., Wang G., Zeng T. (2023): Preparation of phosphorus-modified biochar for the immobilization of heavy metals in typical lead-zinc contaminated mining soil: performance, mechanism and microbial community. Environmental Research, 218: 114769.

Shi A., Hu Y., Zhang X., Zhou D., Xu J., Rensing C., Zhang L., Xing S., Ni W., Yang W. (2023a): Biochar loaded with bacteria enhanced Cd/Zn phytoextraction by facilitating plant growth and shaping rhizospheric microbial community. Environmental Pollution, 327: 121559.

Shi L., Li J., Palansooriya K., Chen Y., Hou D., Meers E., Tsang D., Wang X., Ok Y. (2023b): Modeling phytoremediation of heavy metal contaminated soils through machine learning. Journal of Hazardous Materials, 441: 129904.

Sinduja M., Sathya V., Maheswari M., Dinesh G., Dhevagi P., Prasad S., Boomiraj K., Kalpana P. (2023): Phytoextraction potential of *Chrysanthemum* and Cumbu Napier hybrid grass to remediate chromium-contaminated soils using bioamendments. International Journal of Environmental Research, 17: 8.

Song W., Wang J., Zhai L., Ge L., Hao S., Shi L., Lian C., Chen C., Shen Z., Chen Y. (2022): A meta-analysis about the accumulation of heavy metals uptake by *Sedum alfredii* and *Sedum plumbizincicola* in contaminated soil. International Journal of Phytoremediation, 24: 744–752.

Wang Q., Wang B., Ma Y., Zhang X., Lyu W., Chen M. (2022a): Stabilization of heavy metals in biochar derived from plants in antimony mining area and its environmental implications. Environmental Pollution, 300: 118902.

Wang Z., Luo P., Zha X., Xu C., Kang S., Zhou M., Nover D., Wang Y. (2022b): Overview assessment of risk evaluation and treatment technologies for heavy metal pollution of water and soil. Journal of Cleaner Production, 379: 134043.

Wang Z., Sun F., Yang T., Liu X., Jiang Q., Shang H., Zheng C. (2025): Wind erosion control of bare surface soil in arid mining area by cyanobacterial inoculation and biochar amendment. Catena, 250: 108765.

Wei J., Zheng X., Liu J. (2023): Modeling analysis of heavy metal evaluation in complex geological soil based on Nemerow index method. Metals, 13: 439.

Xu X., Wu Y., Wu X., Sun Y., Huang Z., Li H., Wu Z., Zhang X., Qin X., Zhang Y., Deng J., Huang J. (2022): Effect of physicochemical properties of biochar from different feedstock on remediation of heavy metal contaminated soil in mining area. Surfaces and Interfaces, 32: 102058.

Yang Q., Wang Y., Zhong H. (2021): Remediation of mercury-contaminated soils and sediments using biochar: a critical review. Biochar, 3: 23–35.

Yang X., Liu L., Tan W., Liu C., Dang Z., Qiu G. (2020): Remediation of heavy metal contaminated soils by organic acid extraction and electrochemical adsorption. Environmental Pollution, 264: 114745.

Yu C., Peng X., Yan H., Li X., Zhou Z., Yan T. (2015): Phytoremediation ability of *Solanum nigrum* L. to Cd-contaminated soils with high levels of Cu, Zn, and Pb. Water, Air, and Soil Pollution, 226: 147.

Zhang Y., Gong J., Cao W., Qin M., Song B. (2023): Influence of biochar and fulvic acid on the ryegrass-based phytoremediation of sediments contaminated with multiple heavy metals. Journal of Environmental Chemical Engineering, 11: 109446.

Zeng Q., Shen L., Feng T., Hao R. (2022): Investigation of the distribution of heavy metals in the soil of the Dahuangshan mining area of the Southern Junggar Coalfield, Xinjiang, China. Minerals, 12: 1332.

Zhao Z., Zhang H., Duan Y., Sun L., Pang X., Wang X., Tang X. (2024): Varieties of P fractions in biochar-amended reconstructed soils as impacted by freeze-thaw interference. Journal of Environmental Management, 366: 121839.

Zhu Y., Ge X., Wang L., You Y., Cheng Y., Ma J., Chen F. (2022): Biochar rebuilds the network complexity of rare and abundant microbial taxa in reclaimed soil of mining areas to cooperatively avert cadmium stress. Frontiers in Microbiology, 13: 972300.

Received: November 3, 2026
Accepted: April 4, 2026