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RESEARCH ARTICLE

Application of biochar and compost improved soil properties and enhanced plant growth in a Pb–Zn mine tailings soil

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Abstract

This study evaluated the effect of biochar and compost on physiochemical properties, heavy metal content, microbial biomass, enzyme activities, and plant growth in Pb–Zn mine tailings. In this study, a pot experiment was conducted to evaluate the effects of biochar, compost, and their combination on the availability of heavy metals, physicochemical features, and enzyme activities in mining soil. Compared to separate addition, the combined application of biochar and compost was more effective to improve soil pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP), and potassium (AK). All amendments significantly decreased $CaCl_2$-extractable Pb, Zn, Cu, and Cd. Soil enzyme activities were activated by biochar and compost. Meanwhile, the addition of biochar and compost decreased heavy metal content in plant tissues and increased plant biomass. Pearson's correlation analysis showed that plant biomass was positively correlated with nutrient levels, microbial biomass, and enzyme activities, whereas it was negatively correlated with $CaCl_2$-extractable heavy metals. These results enhance our understanding of the ecological functions of biochar and compost on the restoration of mining soil and reveal the potential benefit of organic amendments on the improvement of mining soil quality.

Keywords Heavy metal · Microbial biomass · Enzyme activity · Compost · Biochar

Introduction

Mine tailings are hazardous solid wastes produced during metalliferous ore mining and smelting activities. The majority of tailings are mainly stored on land, occupying large areas (Karaca et al. 2018). In addition, mine tailing areas generally lack vegetation cover and thus are more vulnerable to wind and water erosion, causing pollution of surface soils and groundwater (Zerizghi et al. 2022). Ecological restoration of mine tailings becomes the key to guaranteeing sustainable development for the metalliferous metal industries.

Mine tailings commonly exhibit adverse properties such as extreme pH, high levels of heavy metals, and lack of organic matter and fertility (Wang et al. 2017). Reducing the toxicity of the heavy metals and improving the physicochemical and biological properties of mine tailings are critical to ecological restoration of mine tailings. Biochar and composts are widely used in the remediation of heavy metal-contaminated soils as they are cheap, effective, and easy to obtain (Tang et al. 2020; Liang et al. 2017). Biochar is an organic carbon-rich material produced from the pyrolysis of agricultural residues under anaerobic conditions, which is characterized by high pH and cation exchange capacity, large specific surface area, and abundant functional groups (Panahi et al. 2020). Compost is produced by spontaneous microbial oxidation of straw wastes from agriculture, livestock manures, and other organic wastes, which contains large amounts of humic acid and is rich in organic carbon and nutrients (Cesaro et al. 2015). Based on these unique properties,

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biochar and compost both play a good performance in the reduction of the bioavailability and mobility of heavy metals in contaminated soils (Ji et al. 2022). For instance, Ahmad et al. (2012) indicated that the application of biochar derived from mussel shells and cow bones can reduce the bioavailable Pb by over 70% in shooting range soil. Biochar derived from *Miscanthus* straw was reported to be effective in decreasing the available Cd, Zn, and Pb in contaminated soils (Houben et al. 2013). Similarly, Gusiatin and Kulikowska (2016) also found that sludge compost reduced the bioavailability of Cd, Ni, and Zn in contaminated soil. Furthermore, Chen et al. (2010) reported that the addition of a poultry manure compost decreased both water-soluble and exchangeable Cd in Cd-contaminated soil, thereby reducing the Cd uptake by pakchoi crop.

Microbial biomass carbon and nitrogen are active components in the soil organic carbon and nitrogen pools, reflecting the importance of their turnover (Singh and Gupta 2018). Soil enzymes are proteinaceous macromolecules with biocatalytic ability which play critical roles in biochemical processes including organic matter mineralization and decomposition, redox reactions, and nutrient cycling (Luo et al. 2017). Enzyme activities are important biological indicators to evaluate the soil quality in heavy metal-contaminated soil (Tang et al. 2019). Biochar and compost have positive impacts on the activities of soil enzymes. For example, straw biochar increased urease and catalase activities in polymetallic-contaminated soil (Yang et al. 2016). Jia et al. (2017) found that the activities of urease and invertase in a Cd/Cu-contaminated soil both increased by 187.5% and 67.9%, followed by wheat straw biochar application. Similar to biochar, compost also has a good promotion on enzyme activities. Bhattacharyya et al. (2005) revealed that municipal solid waste compost activated the activity of urease and acid phosphatase in soil contaminated with Cd, Pb, Cu, and Zn. Garau et al. (2019) found that biosolid compost addition significantly increased dehydrogenase activity by nearly 20 times. Biochar and compost amendments can therefore accelerate the recovery of microbial biomass and enzyme activities by increasing nutrient availability and reducing that of heavy metals in contaminated soils. However, it is surprising that little information is available on the effects of biochar and compost on the improvement of microbial properties and enzyme activities in mine tailing soils. In addition, the relationships between enzyme activities and physicochemical properties, as well as bioavailability of heavy metals have been rarely evaluated simultaneously.

The aims of the present study were as follows: (1) to determine the impact of the effects of biochar, compost, and their combination on the availability of heavy metal in an abandoned Pb–Zn tailings; (2) to investigate the improvement of microbial biomass and enzyme activities following the application of biochar and compost; (3) to investigate the relationships between enzyme activities and physicochemical properties and the bioavailability of heavy metals.

Materials and methods

Soil sampling and characterization of amendments

Samples were collected from the surface horizon (0–20 cm) in an abandoned Pb–Zn tailings (E113°8′8.63″; N25°41′41″) area in Chenzhou City, Hunan Province, PR China. The soil was severely polluted by heavy metals due to past intensive mining and metallurgical activities, among which Pb, Zn, Cu, and Cd were the main polluted heavy metal. According to field investigation, this soil was mainly contaminated with Pb, Zn, Cu, and Cd (Table 1). After removing gravel and plant residues, the samples were placed in sterile sealed bags and transported to the laboratory. Biochar was obtained from rice straw using a tubular carbonization furnace under hypoxia conditions (500 °C, for 3 h) and ground to pass through a 2-mm sieve (Liang et al. 2017). Compost was obtained from agricultural waste (rice straw, vegetable leaves, etc.) according to previous studies (Liang et al. 2017). The main physicochemical characteristics of the untreated soil, biochar, and compost were presented in Table 1.

Experimental design and planting trial

Four treatments were prepared as follows: (1) CK, no addition; (2) TB, 2% biochar; (3) TC, 2% compost; and (4) TBC, 2% biochar and 2% compost. Three replicates were set for each treatment. Amendments were thoroughly mixed with mine tailings soil (1 kg) and then placed in 12 pots for each treatment (48 pots in total). The pots were perforated at the base with ten 3 mm diameter holes for drainage (a plastic

Table 1 Physicochemical properties of soils and amendment

Soil properties	Untreated	Biochar	Compost
pH	5.8 ± 0.48b	8.6 ± 0.36a	8.3 ± 0.89a
EC (ds m^{-1})	0.52 ± 0.14b	0.27 ± 0.11b	5.8 ± 1.2a
Total organic C (g kg^{-1})	5.8 ± 0.76c	468 ± 54a	234 ± 26b
Total N (g kg^{-1})	0.56 ± 0.12c	7.2 ± 0.64b	19 ± 2.4a
Available P (g kg^{-1})	27 ± 3.2c	68 ± 7.3b	137 ± 12a
Available K (g kg^{-1})	42 ± 8.3c	84 ± 15b	136 ± 21a
Total Pb (mg kg^{-1})	521 ± 78a	63 ± 25b	42 ± 12b
Total Zn (mg kg^{-1})	1365 ± 341a	316 ± 74b	194 ± 58c
Total Cu (mg kg^{-1})	452 ± 84a	46 ± 11c	87 ± 25b
Total Cd (mg kg^{-1})	25 ± 7.46a	6.8 ± 1.5b	3.4 ± 0.82c
Specific surface area	–	66 ± 4.5	–
Ash (%)	–	54 ± 0.89	–
Moisture (%)	21 ± 1.2b	3.4 ± 0.12c	31 ± 6.4a

Numbers are presented as means ± standard deviations (SD). Different lower case letters indicate significant differences among different treatments ($P < 0.05$)

container with 12 cm diameter and 11 cm depth). We placed 40 ryegrass seeds in each pot. The ryegrass was thinned, leaving 20 seedlings with a similar length. All pots were randomly arranged in an artificial climate room and incubated at room temperature (20–25 °C) for 60 days. During the whole incubation period, the water content was maintained at 70% water-holding capacity.

Plant shoot samples were collected on day 60 and dried at 105 °C for 30 min and then at 65 °C to constant weight. The dry weights of all plant samples were recorded. The bulk soil samples were collected on day 15, day 30, and day 60. All soil samples were divided into three parts: one part was air-dried for physicochemical analyses; the second part was stored at 4 °C for the determination of microbial biomass, and the third part was stored at –20 °C for determination of enzyme activities.

Determination of soil physicochemical characteristics

The pH and EC were measured in 1:5 (w/v) aqueous suspension (Zhang et al. 2016). The soil organic carbon (SOC) was determined by potassium dichromate oxidation (Zhang et al. 2016). Total nitrogen (TN) was determined by a semi-trace Kjeldahl method (Zhang et al. 2016). Available phosphorus (AP) was extracted by 0.5 M $NaHCO_3$ (pH 8.5) and determined by UV–visible spectrophotometry (Tang et al. 2020). Available potassium (AK) was extracted by 1 M NH_4OAc (pH 7) and determined by flame spectrophotometry (Tang et al. 2020).

Determination of heavy metal availabilities in soil

Available form of heavy metals was extracted using calcium chloride ($CaCl_2$) (Liang et al. 2017). Briefly, 2 g air-dried soil sub-samples were weighed and loaded into 50-mL centrifugal tubes. Forty milliliters of $CaCl_2$ was added to each tube and shaken at 60 rpm for 24 h in a rotary shaker, followed by centrifugation at 3500 rpm for 20 min. The supernatants were then filtered through 0.45-μm filters. To avoid any subsequent precipitation of heavy metals, the extracted filtrates were acidified with two drops of 1 M HNO_3. The concentrations of Cd, Pb, Cu, and Zn in the supernatants were measured by an inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700, Agilent Technologies, CA, USA).

Determination of microbial biomass and enzyme activities

Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were determined by using the $CHCl_3$ (chloroform) fumigation-K_2SO_4 extraction method (Brookes et al. 1985; Wu et al. 1990). In summary, two sub-samples of 20 g soil were weighed and placed into plastic boxes. One part was fumigated for 24 h at 25 °C with ethanol-free $CHCl_3$ and the other part was incubated under the same conditions without the chloroform. When the fumigation part was completed, the fumigant was removed by using a vacuum compressor. The soil samples were treated with 80 mL of 0.5 M K_2SO_4, shaken for 1 h at 200 rpm, and then filtered. Carbon content and nitrogen content were measured by using an elemental analyzer (Vario EL III Elementar, Germany) and a continuous flow injection analyzer (Seal Analytical AA3, Norderstedt, Germany), respectively.

Four soil enzymes including two C-cycling enzymes (β-glucosidase and invertase) and two N-cycling enzymes (urease and protease) were assayed. The activities of β-glucosidase and invertase were both determined by the 3,5-dinitrosalicylic acid colorimetric method (Guan 1986). Glucose and sucrose were used to measure β-glucosidase and invertase. The activities of β-glucosidase and invertase were expressed as the glucose and sucrose released in 1 g soil samples at 37 °C after 1 h. Urease activity was determined by the indophenol blue colorimetric method, expressed as the ammonia–nitrogen (NH_3-N) released from 1 g tailings samples at 37 °C after 1 h (Guan 1986). The protease activity was determined by the ninhydrin colorimetric method and similarly expressed as the amino acid-nitrogen released from 1 g soil samples at 37 °C after 1 h (Guan 1986).

Determination of heavy metal in plant tissue

Heavy metals in plant samples were determined by nitric acid-perchloric acid digestion method. Briefly, 0.5 g of plant tissue was weighed and placed into a digestion tube. Five milliliters of concentrated nitric acid and perchloric acid were added to the tissue to soak overnight. The digest tubes were then set up in a heating block maintaining the temperature at 90 °C for 30 min, 140 °C for 30 min, and then 180 °C for 1 h. When the tubes were cooled, the digests were filtered through 0.45-μm filters and the tubes were washed with deionized water to maintain the filtrates to a constant volume of 100 mL. Cd, Cu, Pb, and Zn concentrations in the filtrates were determined by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700, Agilent Technologies, CA, USA).

Statistical analysis

The physicochemical characteristics, heavy metal availabilities, microbial biomass, enzyme activities, and plant biomass of the four treatment samples were summarized and analyzed statistically using SPSS software (version 22). The effects of biochar and compost additions on these parameters were tested by one-way analysis of variance (ANOVA). Pearson correlation analysis was also employed to test for correlations between different parameters.

Results and discussion

Effects of amendments on soil physicochemical properties

Summarized physicochemical properties of the soil samples were presented in Fig. 1. The untreated tailings soils exhibited low pH and nutrient contents. The pH of tailing soil increased significantly in all the amended treatments, with the highest values in the TBC treatment. There was no significant difference between the TB and TC treatment ($P > 0.05$). EC also significantly increased in the TC and TBC treatments ($P < 0.05$), whereas it decreased in the TB treatment on day 30 and day 60 ($P < 0.05$). Compared with the TC treatment, EC in the TBC treatment showed a slight increase on day 15 ($P > 0.05$), but a slight decrease on day 30 and day 60 ($P > 0.05$). The biochar, compost, and their combination increased the content of SOC, TN, AP, and AK in tailings soil. Significant increases in SOC were observed in all treatments, following the order TBC > TB > TC > CK ($P < 0.05$). For TN, AP, and AK, significant increases in SOC were observed in TC and TBC treatment ($P < 0.05$), with the highest values in the TBC treatment. No significant difference was observed between CK and TB treatment ($P > 0.05$).

Tailings soil was generally characterized by an extreme pH and a low nutrient content which severely hindered the development of a vegetation cover (El Rasafi et al. 2021). The improvement of tailings soil is fundamental to the ecological restoration of tailings soil. In our study, the

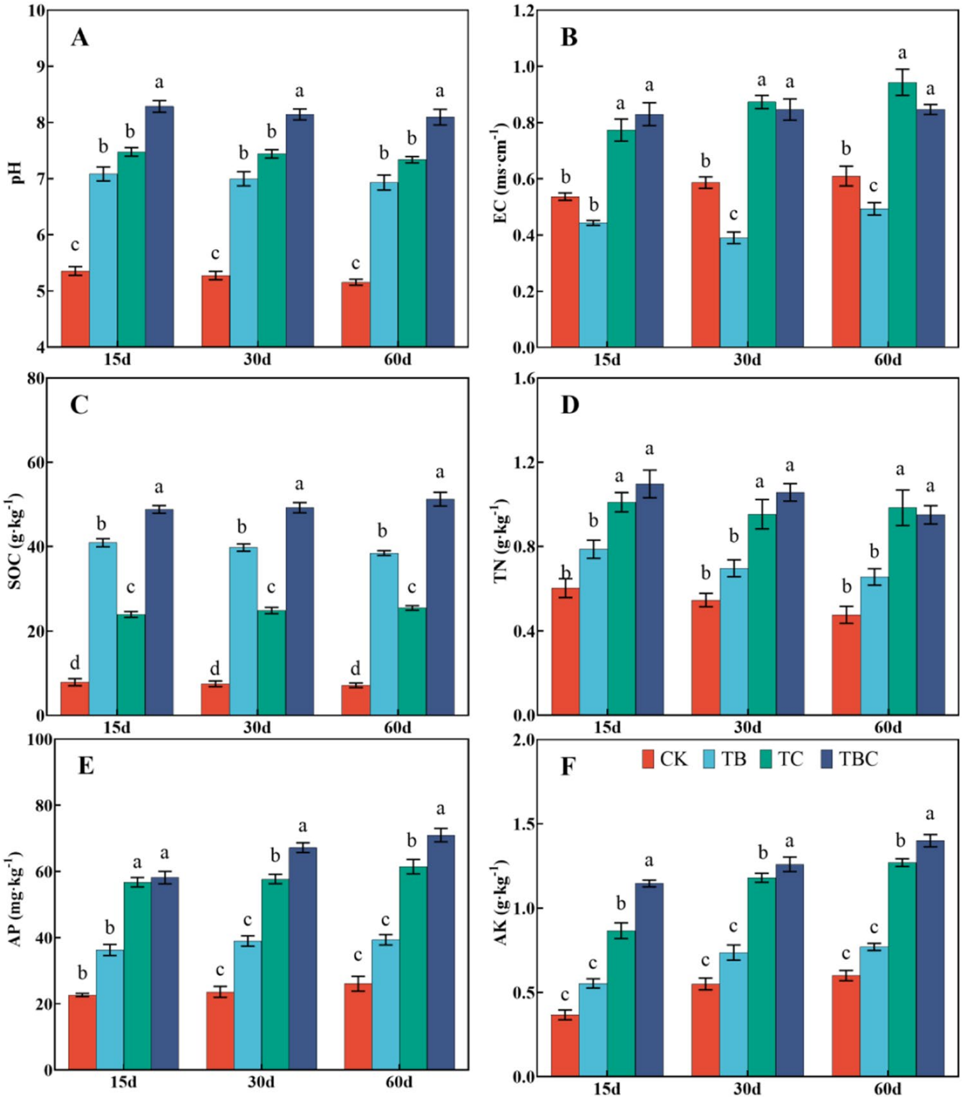

Fig. 1 Effect of amendments on physicochemical properties in tailings soil under different treatments: **A** pH, **B** EC, **C** SOC, **D** TN, **E** AP, **F** AK. Different lower case letters indicate significant differences between treatments ($P < 0.05$)

application of biochar and compost significantly increased soil pH (Fig. 1), which coincided with the previous studies (Clemente et al. 2006; Chen et al. 2013; Ibrahim et al. 2016; Tang et al. 2020). Biochar is commonly alkaline, which is caused by the formation of carbonates and phosphates during the pyrolysis process (Li et al. 2019). The pH of biochar and compost in our study was 8.63 and 8.37, respectively, both significantly higher than that of the untreated mine tailings soil (Table 1). The highest pH achieved in the combination of biochar and compost may be related to their interactions. On one hand, biochar provides a favorable environment for microbial growth and promotes microbial proliferation by the selective adsorption of organic matter on the biochar surface and pores (Khan et al. 2016). On the other hand, the compost promotes the formation of oxygen-containing functional groups on the surface of the biochar by a complex interaction of oxidation and sorption processes (Wiedner et al. 2015), which can react with more proton (H^+) in the tailings soil and thereby increase soil pH.

The application of biochar and compost all significantly increased SOC, which was consistent with previous studies (Chen et al. 2013; Abujabhah et al. 2016; Gusiatin and Kulikowska 2016; Arif et al. 2018; Liang et al. 2017). The remediation materials were rich in organic carbon. The organic carbon content of biochar (468 g kg^{-1}) and compost (235 g kg^{-1}) were orders of magnitude higher than that in mine tailings soil (5.8 g kg^{-1}). In addition, biochar can adsorb organic molecules and promote their polymerization through surface catalytic activity and thus improve the organic carbon content of the soil (Song et al. 2019). The addition of biochar and compost could significantly increase the carbon content in mine tailings soil. For TN, AP, and AK, the addition of biochar and compost increased the content of TN, AP, and AK, but significant increases were only observed in the compost and biochar-compost treatments (Fig. 1). On one hand, the high content of TN, AP, and AK in compost directly increased their content in mine tailings soil (Table 1). On the other hand, biochar could reduce the leaching losses of N/P/K by providing attachment sites and increasing cation exchange capacity (Xu et al. 2016). In addition, biochar enhanced microbial activity and therefore accelerated the mineralization of organic carbon, which simultaneously released mineral N/P/K (Fu et al. 2022).

Effects of amendments on the availability of heavy metals

Heavy metal toxicity is the main limiting factor for the sustainable development of plant communities on mine tailing soils (Karaca et al. 2018; Sun et al. 2018). The extractable heavy metals are readily taken up by plants and are commonly used to evaluate heavy metal toxicities (Liang et al. 2017). The content of $CaCl_2$-extractable Pb, Zn, Cu, and Cd are shown in Fig. 2. In the unamended treatment, the content of $CaCl_2$-extractable Pb, Zn, Cu, and Cd was 14.8 mg·kg^{-1}, 27.7 mg·kg^{-1}, 64.2 mg·kg^{-1}, and 0.6 mg·kg^{-1}, respectively. The addition of biochar and compost reduced the content of Pb, Zn, Cu, and Cd decreased by 33–60%, 28–62%, 33–73%, and 24–57%, respectively. Previous studies have also shown that the application of biochar and compost alone or in combination with all decreased extractable concentrations of Pb, Zn, Cu, and Cd in tailings soil (Ibrahim et al. 2016; Gusiatin and Kulikowska 2016; Beesley et al. 2010). For example, Ibrahim et al. (2016) indicated that biochar derived from rice husk significantly decreased the concentrations of available Cr, Cd, Pb, and Zn in contaminated soil. Available Cd and Zn concentrations have also been reported to be effectively reduced by the application of sewage sludge compost (Gusiatin and Kulikowska 2016). Beesley et al. (2010) found that the addition of biochar and green waste compost can significantly decrease the concentrations of available Cd and Zn in the soil.

The reduction of heavy metal availabilities may be partly attributed to the direct effects of the applied amendments. Biochar has been widely used in the remediation of heavy metal-contaminated soil due to its good performance in the immobilization of heavy metals (Al-Wabel et al. 2018): (1) biochar has a large specific surface area with high cation exchange capacity, which can adsorb heavy metals; (2) there are amounts of negatively charged functional groups on the large surface of biochar, which can immobilize metal cations by electrostatic interactions and chelation; (3) biochar is rich in phosphate (PO_4^{3-}), carbonate (CO_3^{2-}), and other mineral components (Fe–Mn oxides), which can adsorb and precipitate heavy metals; (4) biochar can regulate the soil redox potential by increasing soil pH and organic matter content and thus reduce the bioavailability of heavy metals.

Similar to biochar, the compost also mainly passivates heavy metals by adsorption, precipitation, and redox changes. Compost contains varying amounts of carboxyl, carbonyl, phenolic hydroxyl, and alcohol hydroxyl functional groups, which can complex with heavy metal ions to form organic-metal complexes and thus stabilize heavy metals (Chien et al. 2006). The humus in compost can bind metal cations to form stable organometallic complexes and therefore reduce the mobility and bioavailability of heavy metals (Garciamina 2006). Compost contains large amounts of organic matter, which can change the redox potential in soil and indirectly alter the form of heavy metals.

The change of physicochemical properties induced by biochar and compost is another important factor affecting the availability of heavy metals. In the present study, $CaCl_2$-extractable Pb, Zn, Cu, and Cd all showed a negative correlation with pH, SOC, TN, AP, and AK (Table 2), indicating that pH increase and nutrient promotion may help to alleviate the heavy metal toxicity on plant growth.

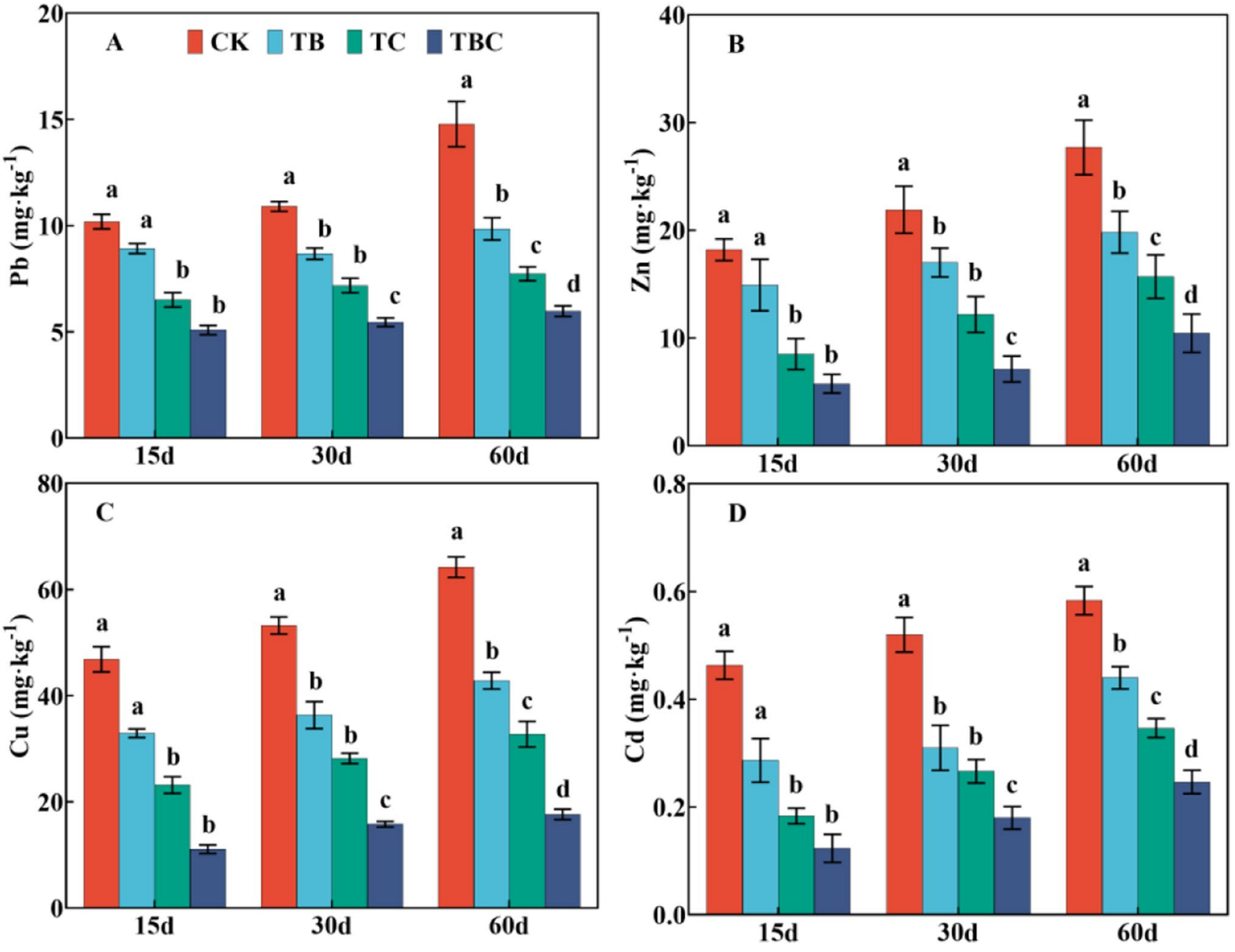

Fig. 2 Effect of amendments on the heavy metal availability in soil samples under different treatments: **A** Pb, **B** Zn, **C** Cu, **D** Cd. Different lower case letters indicate significant differences between treatments ($P < 0.05$)

An increase in AP results in a decrease in the availability of heavy metals which was possibly arisen by precipitation and complexation as insoluble phosphates (Ahmad et al. 2012). Soil organic matter can act as an important adsorbent for heavy metals because it contains important functional groups, such as –COOH and –OH which can easily bind metal ions and form organic-metal complexes (Chapman et al. 2013; Yang et al. 2016). Moreover, organic matter can have an impact on the solubility of metals through hydrolysis, oxidation, and depolymerization (Gusiatin and Kulikowska 2016).

Table 2 Correlation coefficients between soil properties and the $CaCl_2$-extractable heavy metals

	$CaCl_2$-Pb	$CaCl_2$-Zn	$CaCl_2$-Cu	$CaCl_2$-Cd
pH	−0.95**	−0.87**	−0.96**	−0.89**
EC	−0.58	−0.46	−0.56	−0.41
SOC	−0.71*	−0.58	−0.76*	−0.69*
TN	−0.88**	−0.82**	−0.86**	−0.82**
AP	−0.84**	−0.72*	−0.81**	−0.73*
AK	−0.75*	−0.61*	−0.73*	−0.58

Significance levels: *, $P < 0.05$; **, $P < 0.01$

Effects of amendments on microbial biomass and enzyme activity

The microbial biomass carbon (MBC) and nitrogen (MBN) were presented in Fig. 3. The addition of biochar and compost significantly increased both MBC and MBN in the mine tailings soil. The combination of biochar and compost resulted in the greatest increase, followed by compost and biochar ($P < 0.05$). Compared to the unamended treatment on day 60, the MBC and MBN increased by 35% and 34% (TB), 130% and 126% (TC), and 151% and 234% (TBC), respectively.

Glucosidase (GLU), invertase (INV), urease (URE), and protease (PRO) were measured to characterize the dynamic changes of microbial activities in the mine tailing soil following biochar and compost addition (Fig. 4). Compared to CK treatment, TB significantly decreased the activities of glucosidase and protease on day 60 ($P < 0.05$), whereas significantly increased urease activity on day 60 ($P < 0.05$). Compared to the CK and TB treatment, TC and TBC significantly increased the activities of all enzymes ($P < 0.05$) and TC had higher enzyme activities than that in TBC treatment (except for urease).

The microbial biomass and enzyme activities were significantly promoted after the application of biochar and compost. Biomass oils and unstable compounds produced during biochar pyrolysis are adsorbed to its surface and provide the main substrate for microbial growth and metabolism (Cheng et al. 2006). The porous structure of biochar also provides a suitable substrate for the growth and reproduction of microorganisms (Amoakwah et al. 2022). In addition, biochar has a strong adsorption capacity for inorganic nutrients and soluble organic carbon, which provides adequate nutrients for microbial growth and metabolism (Zavalloni et al. 2011).

In addition to the direct effects of biochar and compost on soil structure, the improvements in soil physicochemical properties and the reduction of heavy metals induced by soil additives may also affect microbial biomass and enzyme activities. In the present study, the microbial biomass carbon and nitrogen (MBC and MBN) and enzyme activities (GLU,

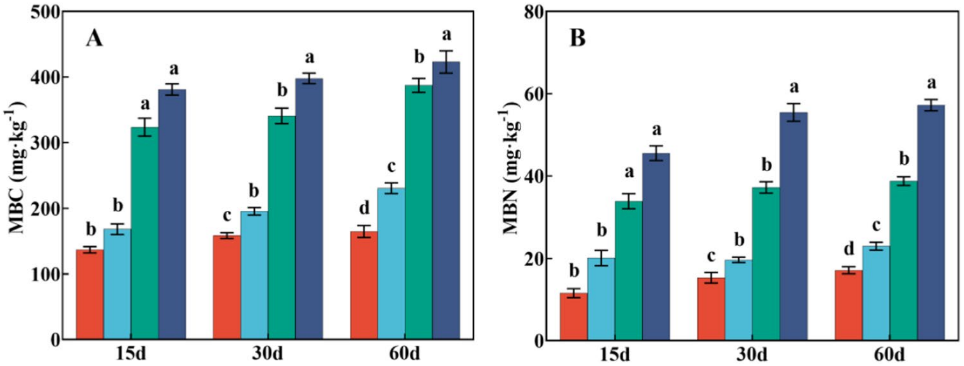

Fig. 3 Effect of amendments on the microbial biomass in soil samples under different treatments: **A** MBC, **B** MBN. Different lower case letters indicate significant differences between treatments ($P < 0.05$)

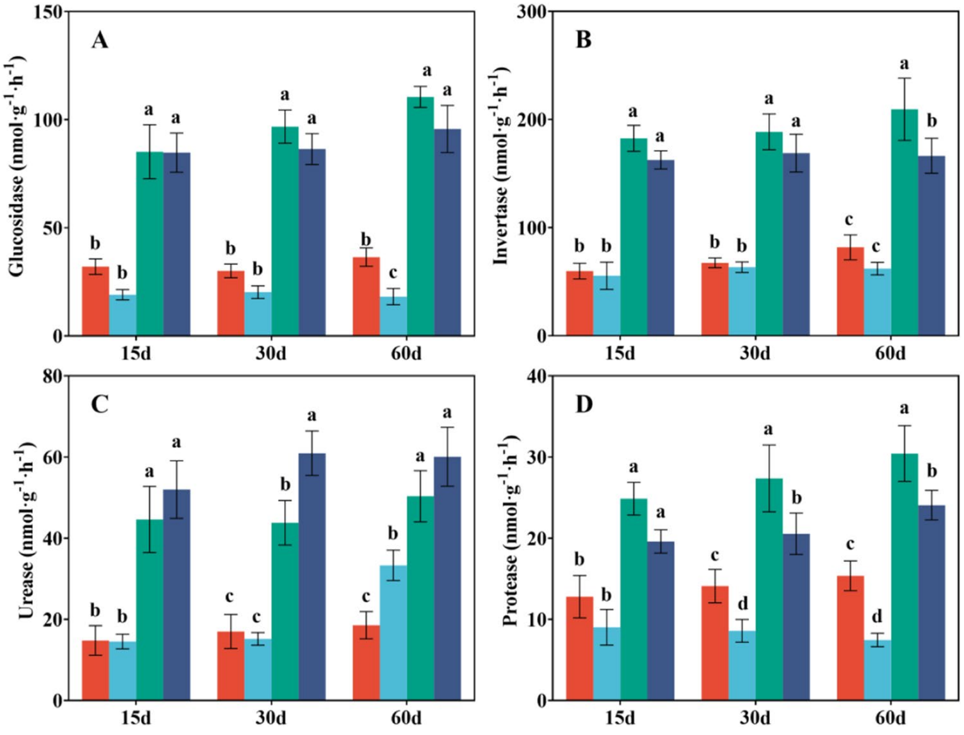

Fig. 4 Effect of amendments on the enzyme activities in mining soil under different treatments. **A** Glucosidase, **B** invertase, **C** urease, **D** protease. Different lower case letters indicate significant differences between treatments ($P < 0.05$)

INV, URE, and PRO) showed significantly positive correlation with EC, TN, AP, and AK ($P < 0.05$) (Table 3). In addition, MBC and MBN showed significantly negative correlation with $CaCl_2$-extractable Pb, Zn, Cu, and Cd ($P < 0.05$). The activities of all selected enzymes (GLU, INV, URE, and PRO) were negatively correlated with $CaCl_2$-extractable Pb, Cu, and Cd ($P < 0.05$) (Table 3). These results indicated that the decrease in the availability of heavy metals and the increase in nutrient status would contribute to microbial recovery, by increasing the microbial population and improving extracellular enzyme activities. Previous studies have shown that the availability and quality of soil nutrients have great impacts on soil microbial biomass and enzyme activities, which may be promoted by high-nutrient supplements, whereas they are inhibited when nutrient levels are low (Xu et al. 2015; Liu et al. 2017; Hu et al. 2014). Supplementation of N, P, and K may alleviate any nutrient limitation of microbial metabolism and therefore enhance the metabolic activities of microorganisms, including the secretion of extracellular enzymes (Liu et al. 2017). The decrease of available heavy metal content may also result in a promotion of enzyme activities as high concentrations inhibit soil enzyme activities due to the metal ions reacting with sulfhydryl groups, chelating with substrates, or reacting directly with enzyme substrates (Hu et al. 2014).

Effects of amendments on the growth of ryegrass

The ryegrass biomass under different treatments was presented in Table 4. Both biomass and plant height were significantly increased in the amended treatments ($P < 0.05$), indicating that the application of biochar and compost stimulated plant growth. Compared to the CK treatment, the ryegrass biomass increased by 175% (TB), 353% (TC), and 425% (TBC), respectively (Fig. 5).

The content of heavy metals in plant was summarized in Table 5. In the control treatment, the content of Pb, Zn, Cu, and Cd was 30.1 $mg \cdot kg^{-1}$, 57.7 $mg \cdot kg^{-1}$, 129.6 $mg \cdot kg^{-1}$, and 3.8 $mg \cdot kg^{-1}$, respectively (Table 4). The addition of biochar and compost decreased the content of Pb, Zn, Cu, and Cd by 25–62%, 45–65%, 47–75%, and 23–80%, respectively (Table 4). The lowest content of Pb, Zn, Cu, and Cd were all observed in TBC treatment, followed by TC treatment and TB treatment (Table 4). These results indicated that biochar and compost inhibited the uptake of Pb, Zn, Cu, and Cd from the mine tailing soil to plants, and their combination achieved the greatest effect.

Table 4 Effects of biochar and compost on the concentrations of heavy metals in plant dry matter

Treatment	Pb ($mg \cdot kg^{-1}$)	Zn ($mg \cdot kg^{-1}$)	Cu ($mg \cdot kg^{-1}$)	Cd ($mg \cdot kg^{-1}$)
CK	30 ± 5.5a	57 ± 8.8a	129 ± 16a	3.7 ± 0.41a
TB	14 ± 3.1b	31 ± 6.4b	69 ± 6.46b	2.8 ± 0.8b
TC	22 ± 3.9c	29 ± 5.5b	52 ± 5.95c	1.7 ± 0.51c
TBC	11 ± 2.1d	20 ± 2.9c	32 ± 4.14d	0.74 ± 0.22d

Numbers are presented as means ± standard deviations (SD). Different lower case letters indicate significant differences between treatments ($P < 0.05$)

Plant biomass was positively correlated with pH, EC, SOC, GLU, INV, and PRO ($P < 0.05$) and strongly correlated with TN, AP, AK, MBC, MBN, and URE ($P < 0.01$) (Table 5). A negative correlation ($P < 0.01$) was detected between plant biomass and all heavy metal content (Table 5). The content of Pb, Zn, Cu, and Cd in plant was negatively correlated with pH, EC, SOC, GLU, INV, and PRO ($P < 0.05$), but was positively correlated with TN, AP, AK, MBC, and MBN, and URE ($P < 0.01$) (Table 5). The content of Pb, Zn, Cu, and Cd in plant was positively correlated with $CaCl_2$-extractable Pb, Zn, Cu, and Cd content in the mine tailing soils ($P < 0.01$) (Table 5).

The addition of biochar and compost promoted plant growth on the mine tailings soil. This may be attributed to the increased nutrient status, decreased available heavy metal content, and increased microbial biomass and enzyme activities (Table 5). In addition to low nutrient element status, heavy metal toxicity is also often a primary factor

Table 3 Correlation coefficients between physicochemical properties, heavy metals, and microbial properties in tailings soil

	MBC	MBN	GLU	INV	URE	PRO
pH	0.87**	0.91**	0.56	0.63*	0.82**	0.56
EC	0.69*	0.72**	0.88**	0.79**	0.82**	0.87**
SOC	0.68*	0.75**	0.19	0.13	0.57	0.26
TN	0.82**	0.83**	0.64*	0.63*	0.68*	0.62*
AP	0.95**	0.94**	0.67*	0.66*	0.86**	0.64*
AK	0.93**	0.91**	0.71*	0.71*	0.89**	0.68*
$CaCl_2$-Pb	−0.82**	−0.86**	−0.56	−0.62	−0.75**	−0.56
$CaCl_2$-Zn	−0.68*	−0.72**	−0.51	−0.55	−0.58	−0.47
$CaCl_2$-Cu	−0.81**	−0.85**	−0.52	−0.58	−0.76*	−0.51
$CaCl_2$-Cd	−0.68*	−0.74**	−0.41	−0.48	−0.63*	−0.41

Significance levels: *, $P < 0.05$; **, $P < 0.01$

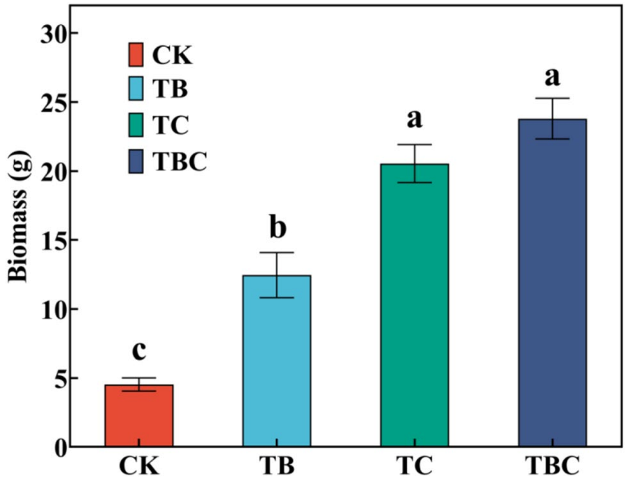

Fig. 5 Effect of amendments on the biomass of ryegrass under different treatments. Different lower case letters indicate significant differences between treatments ($P < 0.05$)

limiting plant growth in mine tailings soils. All the heavy metal concentrations in plant biomass decreased to different degrees in our biochar and compost-treated soils.

Our study has confirmed that the addition of biochar and compost reduced the toxicity of the heavy metals present in the mine tailing soil, as well as improved the content of organic carbon and nutrient status. The biochar and compost also promoted the recovery of microbial biomass and enzyme activities, which facilitated plant growth in this short-term growth trial. However, the long-term effects of the organic amendments on the immobilization of heavy metals and the establishment of a diverse, functional, and stable microbial community still need to be investigated.

Table 5 Correlation coefficients between plant parameters and soil characteristics

Tailings properties	Plant parameters				
	Biomass	Pb	Zn	Cu	Cd
pH	0.91**	−0.86**	−0.83**	−0.95**	−0.83**
EC	0.63*	−0.61	−0.31	−0.59*	−0.54
SOC	0.69*	−0.59*	−0.73**	−0.74**	−0.67*
TN	0.84**	−0.73**	−0.76**	−0.85**	−0.85**
AP	0.88**	−0.86**	−0.87**	−0.98**	−0.86**
AK	0.95**	−0.85**	−0.86**	−0.94**	−0.88**
$CaCl_2$-Pb	−0.91**	0.89**	0.86**	0.93**	0.83**
$CaCl_2$-Zn	−0.82**	0.84**	0.93**	0.91**	0.88**
$CaCl_2$-Cu	−0.93**	0.89**	0.84**	0.92**	0.85**
$CaCl_2$-Cd	−0.91**	0.85**	0.91**	0.95**	0.88**
MBC	0.91**	−0.81**	−0.75**	−0.95**	−0.84**
MBN	0.87**	−0.83**	−0.82**	−0.93**	−0.88**
GLU	0.57	−0.65*	−0.43	−0.55	−0.58
INV	0.61*	−0.66*	−0.41	−0.54	−0.53
URE	0.95**	−0.92**	−0.81**	−0.93**	−0.81**
PRO	0.61*	−0.63*	−0.43	−0.54	−0.55

Significance levels: *, $P < 0.01$ is **; *, $P < 0.05$

Conclusion

The addition of biochar and compost improved the physicochemical properties, reduced available heavy metal concentrations, promoted enzyme activities in mining soil, and thus promoted plant growth. The ryegrass biomass yields significantly increased while we conducted the application of biochar and compost, especially in their combination. Additionally, the biochar and compost all significantly reduced the availability of Pb, Zn, Cu, and Cd in mining soil. Moreover, the biochar and compost significantly increased nutrient contents, microbial biomass, and enzyme activities in mining soil. Plant biomass was significantly increased by SOC and TN, whereas decreased by extractable heavy metals. This study suggested that the application of biochar and compost reduced the bioavailability of heavy metals in mining soil and improved the quality of mining soil and plant.

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Author contribution All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Xuan Bu, Jing Li, Zhihui Ji, Chenggang Wang, Xiao Xiao, Feng-lin Li, Zhuo-hui Wu, and Guanxiong Wu. The first draft of the manuscript was written by Yizhi Cheng and Pu Jia, writing—review and editing was done by Pu Jia and Jin-tian Li, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Available upon request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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