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CO-RECYCLING OF SEWAGE SLUDGE AND GARDEN WASTE BIOCHAR: AS A GROWING MEDIUM FOR LANDSCAPE PLANT

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Highlights

- Co-recycling of biochar & sewage sludge boosts plant growth & soil remediation.
- *Ficus altissima* biochar enhances *Monstera deliciosa* growth & nutrient uptake.
- 3% biochar treatment shows optimal results for landscape plant cultivation.
- Sustainable urban waste disposal: biochar & sewage sludge as soil amendments.

Abstract. Urban greening produces a large amount of garden waste, and the pyrolysis of garden waste into biochar is an effective waste management technology. Biochar has a large specific surface area and soil remediation ability. However, the knowledge about the co-recycling of sewage sludge and garden waste biochar to improve the growth of *Monstera deliciosa* needs to be highlighted. Therefore, we conducted a pot experiment by applying *Ficus altissima* litter-derived biochar (FB) at rates of 0, 1.5, and 3.0% (w/w, CK, FB1.5, and FB3) in soil amended with sewage sludge at 50% (w/w), to improve the soil properties, and further analyzed the effects of FB on growth and heavy metals (HMs) uptake of landscape plant *M. deliciosa*. Results showed in comparison with control setups, the addition of 3% FB treatment in sewage sludge amended soil improved the soil properties and significantly increased *M. deliciosa* dry weight (86.75%), root: shoot ratio (73.23%), N (99.44%), P (116.13%), K (124.40%), Pb (78.81%), and Cu (159.01%) accumulation respectively. In summary, FB3 treatment achieved the best effects in promoting plant growth and soil remediation. These findings revealed that sewage sludge and garden waste biochar could be recycled as amendments for poor acid soils under restoration, a sustainable development path for urban waste disposal.

Keywords: garden waste biochar, sewage sludge recycling, heavy metal, landscape plant, soil amelioration.

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Introduction

As global warming continues to increase, carbon emission reduction has become a common concern for scientists and governments worldwide (Zhang et al., 2021). To mitigate climate change and combat carbon emissions, it is imperative to implement strategies that effectively reduce greenhouse gas emissions while actively sequestering and removing CO_2 from the atmosphere (Lehmann et al., 2021). With the increasing area of urban greening in China, the garden waste of landscaping increased, which generated concern about litter material resourcefulness and low-cost disposal. In recent years, biochar has received wide attention as a soil amendment. Its rich pore structure and large specific surface area can effectively absorb heavy metals (HMs) from the soil. Due to its high carbon content and stability, biochar will reduce CO_2 emissions when it replaces renewable energy sources (Hagenbo et al., 2022). Pyrolyzing garden waste into biochar and incorporating it into contaminated soil is an effective carbon capture and storage technology (Hagenbo et al., 2022). A study showed that gardening waste biochar could reduce the soil's effective cadmium (Cd) content by 26%, 16%, and 9%, respectively (Houssou et al., 2022).

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Biochar pyrolyzed from garden waste could provide soil nutrients and promote plant growth. Pyrolyzing garden waste into biochar is a green biochar compared to other types of biochar. Related studies showed that biochar had positive effects on soil carbon sinks. Hagenbo et al. (2022) estimated that biochar produced from forest harvest residues in Norway could remove 0.41 to 0.78 Tg CO_2 equivalents yr^{-1}, of which 79% could be attributed to increased soil C stock. These values correspond to 9–17% of the emissions of the Norwegian agricultural sector. The remediation activities of different charcoal-based materials for heavy metal-contaminated soils differed. A study found that biochar and peat were beneficial for the sustainable remediation of soil HMs contamination. Interestingly, biochar remediation activities resulted in twice as much soil carbon sink as peat (Yu et al., 2021), and biochar was more stable for long-term carbon sink (Liu et al., 2022a). Besides, the physicochemical characteristics of biochar prepared from different materials differed (Yu et al., 2021; Liu et al., 2022b).

With the development of cities, the amount of urban sewage sludge produced increases yearly. Using sewage sludge as a soil conditioner for landscaping not only solves the problem of sludge stockpiling but also effectively improves soil quality, increases soil fertility, and promotes plant growth (Ibrahim et al., 2022; Liu et al., 2022c), which provides more possibilities for sludge resource utilization. However, HMs in sludge are a key limiting factor for landscape use, and reducing the HMs risk in sludge has become an effective way to improve sludge resource utilization (Chu et al., 2018; Wu et al., 2021). Studies have shown that application of biochar to sludge has significant positive effects on HMs (Erdem, 2021; Sarmah et al., 2023), which can significantly reduce the bioavailable HMs contents and help alleviate their toxic effects and realize the resource utilization of sludge (Gong et al., 2018; Irshad et al., 2020). For example, in a pot experiment, Pandey et al. (2022) recorded a 49.29–78.11% reduction in metal uptake bioavailability to the wheat (*Triticum aestivum*) after applying 3% biochar compared to control setups.

Several studies found that sludge compost is an acceptable growing medium because it improves soil fertility (Wu et al., 2022). In addition, waste can be used as a source of biochar in growing media (Tombarkiewicz et al., 2022), such as tea pruning litter biochar (Sarmah et al., 2023), rice straw and sugarcane bagasse (Farid et al., 2022), and cow manure & reed straw (Yin et al., 2022). Currently, biological strategies for carbon sequestration in soils are widely considered. Garden waste biochar combined with vermicompost may play an innovative role in the container production of decorative plants, and their combination may play an interesting role in partially replacing peat as a growing medium (Álvarez et al., 2018). Increased recycling of garden waste biochar reduces the carbon footprint by replacing peat-based substrates (Liu et al., 2022a).

Due to natural landing and garden pruning every year, South China has a humid climate, rich plant foliage, high rainfall, and abundant reserves of withered material. *Ficus altissima* is a native tree species in southern China, with a long history and a large planting area in landscaping, and its foliage is highly productive and contains many nutrients required for plant growth. The preparation of *F. altissima* litter into biochar for addition to sludge-amended soil is expected to effectively mitigate environmental pollution problems caused by piling or burning litters, weakening the activity of HMs in sludge and reducing the risk of environmental pollution while increasing soil carbon sequestration and improving soil fertility.

Phytoremediation techniques have the advantages of low cost, low soil disturbance, and no secondary pollution and are widely used in the remediation of sludge-amended soil (Wu et al., 2021). *Monstera deliciosa* is an herbaceous plant of the genus *Monstera* in the family *Araceae*, which is highly resistant to stress, grows rapidly, has high ornamental value, is drought and moisture-resistant, tolerates light salinity and has a strong ability to absorb HMs, and is an excellent material for soil HMs remediation. However, previous studies have yet to explore the co-recycling potential of sewage sludge and garden waste biochar to enhance the growth of landscape plants, such as *M. deliciosa*. Additionally, there is a significant knowledge gap regarding the phytoremediation potential of *M. deliciosa*, which needs to be adequately addressed in prior research. Therefore, a pot experiment was conducted to explore the potential of co-recycling of sewage sludge and garden waste biochar in improving the morpho-physiological traits and essential nutrients uptake *M. deliciosa* grown under sewage sludge soil. Hence, it was assumed that (1) applying biochar under sewage sludge amended urban soil would improve phytoremediation efficiency in *M. deliciosa* and (2) identify the main soil property predictors, such as pH, bulk density and total porosity, for the growth changes of landscape plant when biochar was used in sewage sludge amended urban soil. To test this hypothesis, this study analyzed the effects of *F. altissima* litter-derived biochar (FB) at different rates, i.e., 0, 1.5, and 3.0%, respectively, on growth and heavy metal accumulation of *M. deliciosa* grown by potting experiments. These findings were evaluated to decide whether to apply sewage sludge compost as a viable option as a soil supplement, especially for landscape areas, as those plants are not consumed by humans and animals, which aims to provide a reference for urban greening waste utilization and sludge resource treatment.

1. Materials and methods

1.1. Soil and sewage sludge

The soil (20–60 cm) samples (ultisols, pH 5.77) were collected from Foshan Botanical Garden in Foshan City, Guangdong Province, China (23°6′18.32″ N, 113°0′5.43″ E). The sewage sludge (pH 7.52) was collected from the Lvyou Sludge Treatment Plant in Qingyuan City, Guangdong Province, China. They were air-dried at 25–30 °C, ground, and sieved (2 mm). Soil organic matter, pH, bulk density, capillary water holding capacity, and total porosity were further determined according to the procedure mentioned by Wu et al. (2022). The properties of soil and sludge are presented in Table S1.

1.2. Biochar preparation and characterizations

F. altissima litter-derived biochar (pH 12.53) was used in the experiment, prepared from *F. altissima* leaf litter (supplied by Foshan Institute of Forestry). Feedstock materials were air-dried and pyrolyzed at 500 °C under oxygen-limited conditions in a pyrolysis unit (BCP-05, Liaoning Institute of Energy Research Co., Ltd). The average conversion rate of *F. altissima* leaf litter into biochar was 26.8%. After pyrolysis, FB samples were passed through a 2-mm sieve before use. The basic properties of FB are listed in Table S2. The scanning electron microscopy image of FB is listed in Figure 1.

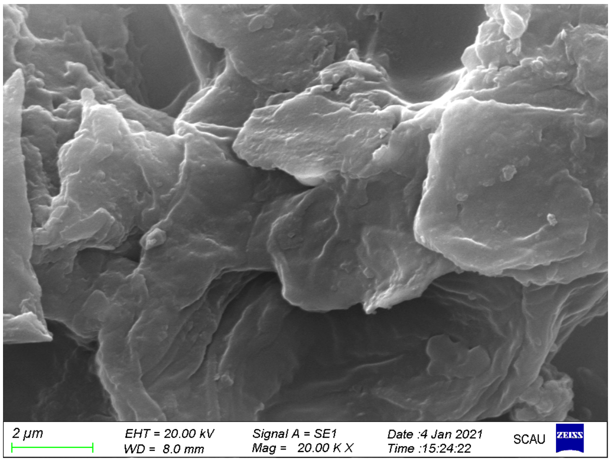


Figure 1. Scanning electron microscopy image of *Ficus altissima* litter-derived biochar (FB) which was produced at 500 °C temperature (scale for measuring scanning electron microscopy was 2.0 μm)

1.3. Pot experiment

Soil and sludge were thoroughly mixed at a ratio of 1:1 (w/w) in plastic pots (3 kg sludge-amended soil/pot). FB was added to the substrate at 0% (w/w), 1.5% (w/w), and 3.0% (w/w), labeled CK, FB1.5, and FB3, respectively. The substrate was watered with deionized water to approximately 70% of field capacity (dynamic monitored by MiniTrase Kit) and left for four weeks for equilibration. Substrate samples were collected from each pot for physicochemical property analysis, and digested by H_2SO_4–$HClO_4$, and then total nitrogen, total phosphorus, total potassium, available phosphorus, and available potassium were further determined according to the procedure mentioned by Wu et al. (2022) (Table 1). The contents of total potassium, available potassium, and available HMs [Cd, lead (Pb), copper (Cu), and zinc (Zn)] content were further determined using atomic absorption spectrometry (AAS, HITACHI JACO6-25, Hitachi Ltd., Japan) (Wu et al., 2022; Pueyo et al., 2008). Standard reference material (GBW07406a) was used to ensure the accuracy of the analytical methods (Liu et al., 2023).

Then, the landscape plant *M. deliciosa*, which has high ornamental value, was selected as the test plant. Healthy and uniform seedlings of *M. deliciosa* were obtained from the Fangcun flower production base in Guangzhou City, Guangdong Province. In March 2020, one seedling of *M. deliciosa* was transplanted into each pot. Three replicates were established for each treatment, and all pots were rinsed with deionized water to maintain approximately 70% of field capacity, which was dynamically monitored using the MiniTrase Kit. The pots were randomly positioned in a greenhouse with a temperature range of 20–30 °C.

1.4. Observations and measurements

In November 2020, we harvested the seedlings of *M. deliciosa*. We measured plant height at harvest of the seedlings. After that, seedlings were separated into shoots and roots, placed in a blast drying oven, and dried to a constant weight to determine plant dry weight (g plant^{-1}) and root: shoot ratio [root weight (g plant^{-1}): shoot weight (g plant^{-1})]. Plant N and K contents (g kg^{-1}) were analyzed by the Kjeldahl method (Bremner & Mulvaney, 1982) and AAS (HITACHI JACO6-25, Hitachi Ltd., Japan), respectively. Plant P content (g kg^{-1}) was measured photometrically after the samples were digested with H_2SO_4–H_2O_2. Plant HMs (Cd, Pb, Cu, and Zn) contents (mg kg^{-1}) were determined quantitatively by the digestion of samples in a microwave digestion system followed by AAS (HITACHI JACO6-25, Hitachi Ltd., Japan) (Alhar et al., 2021) according to the procedure mentioned by Wu et al. (2022).

Plant nutrients accumulation (mg plant^{-1}) = Plant nutrients content (mg g^{-1}) × plant biomass (g plant^{-1}).

Plant HMs accumulation (μg plant^{-1}) = Plant HMs content (mg kg^{-1}) × plant biomass (g plant^{-1}).

1.5. Data analysis

One-way ANOVA and Tukey's multiple range test (using $\alpha = 0.05$ as the significance level) were further used. The ANOVA analyses were performed using the software IBM SPSS Statistics 23.0 (SPSS Inc., New York, USA), and the bar figures were plotted with GraphPad Prism 8 (Systat Software Inc., San Jose, CA, USA). All data are expressed as mean ± standard error (n = 3). Then, we tested the statistical associations using the "ggplot2", "vegan", and "plspm" packages in R 4.2.1 (R Core Team, 2022).

2. Results

2.1. Soil properties and available heavy metals content

All FB treatments increased the soil capillary capacity, total porosity, pH, soil organic matter, total N, total P, total K, available P, and available K content (Table 1). Among all the treatments, FB3 treatment has better-improved soil physicochemical properties. Besides, FB3 treatment significantly minimized soil available Cu content by 14.84% over control ($P < 0.05$) (Figure 2).

2.2. Plant growth and nutrients accumulation

Application of FB at the rate of 3% significantly increased dry weight and root: shoot ratio of *M. deliciosa* seedlings by 86.75 and 73.23%, respectively, over control ($P < 0.05$) (Figures 3, 4). Compared to CK, applying FB at the rate of 3% significantly increased N, P, and K accumulation of *M. deliciosa* by 99.44, 116.13, and 124.40%, respectively ($P < 0.05$).

2.3. Plant heavy metals accumulation

Compared to the control, the application of FB at the rate of 3% increased the Cd, Pb, Cu, and Zn accumulation of *M. deliciosa* by 51.97, 78.81, 159.01, and 103.87%, respectively (Figure 5). Besides, FB1.5 treatment significantly promoted the Zn accumulation of *M. deliciosa* by 170.23% ($P < 0.05$).

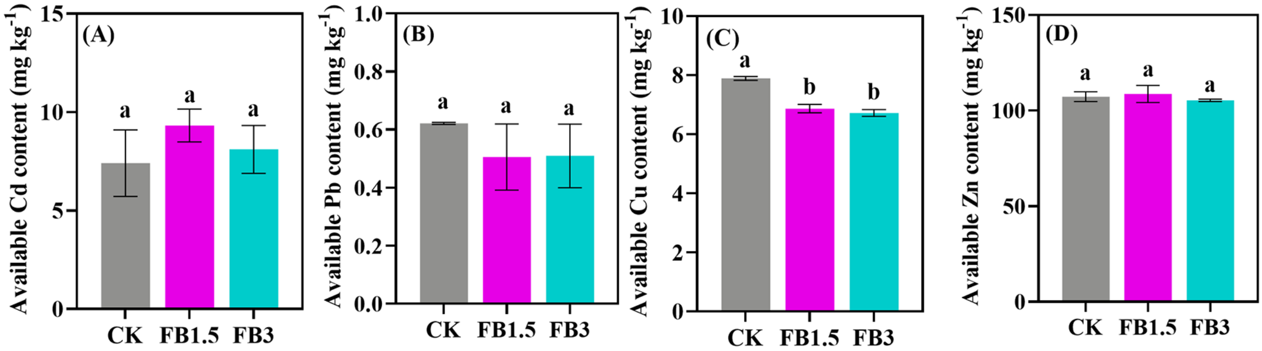


Figure 2. Effects of *Ficus altissima* litter-derived biochar (FB) at different rates i.e., 0, 1.5, and 3.0% (w/w, CK, FB1.5, and FB3), respectively, on soil available Cd content (A), available Pb content (B), available Cu content (C) and available Zn content (D) of *Monstera deliciosa* grown under sewage sludge amended soil. Values are mean ± standard error (n = 3). Different lowercase letters show significant differences between the means ($P < 0.05$)

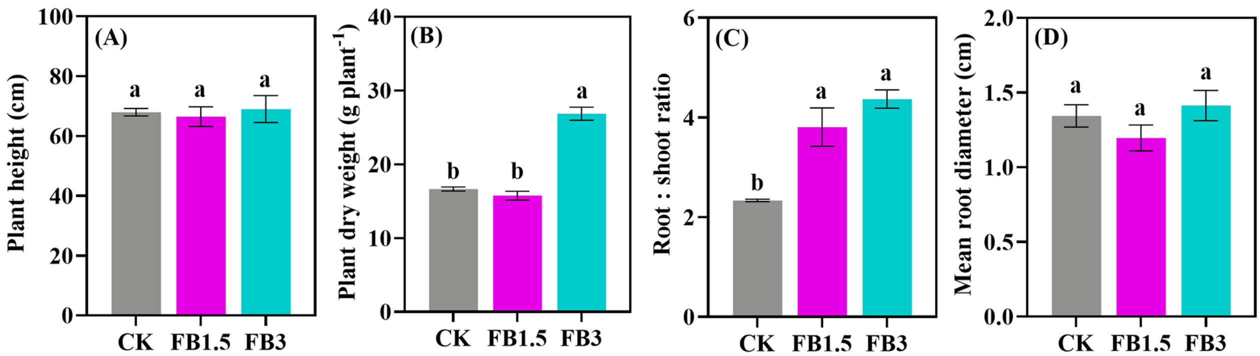


Figure 3. Effects of *Ficus altissima* litter-derived biochar (FB) at different rates i.e., 0, 1.5, and 3.0% (w/w, CK, FB1.5, and FB3), respectively, on plant height (A), plant dry weight (B), root: shoot ratio (C), and mean root diameter (D) of *Monstera deliciosa* grown under sewage sludge amended soil. Values are mean ± standard error (n = 3). Different lowercase letters show significant differences between the means ($P < 0.05$)

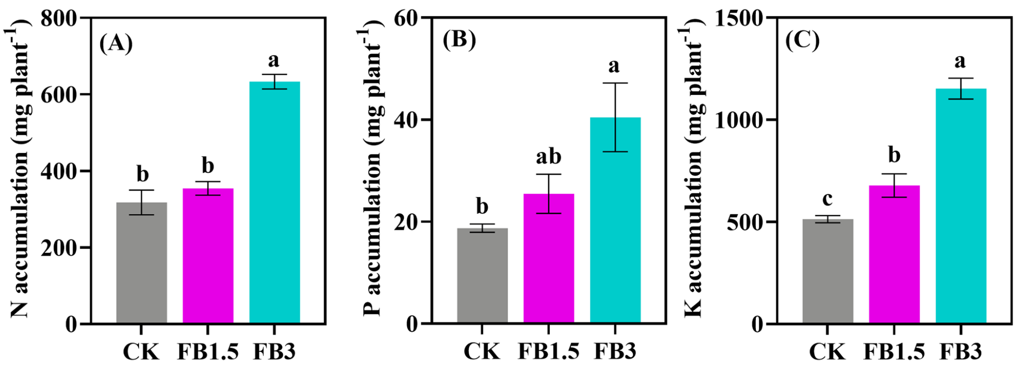


Figure 4. Effects of *Ficus altissima* litter-derived biochar (FB) at different rates i.e., 0, 1.5, and 3.0% (w/w, CK, FB1.5, and FB3), respectively, on plant N accumulation (A), plant P accumulation (B), and plant K accumulation (C) of *Monstera deliciosa* grown under sewage sludge amended soil. Values are mean ± standard error (n = 3). Different lowercase letters show significant differences between the means ($P < 0.05$)

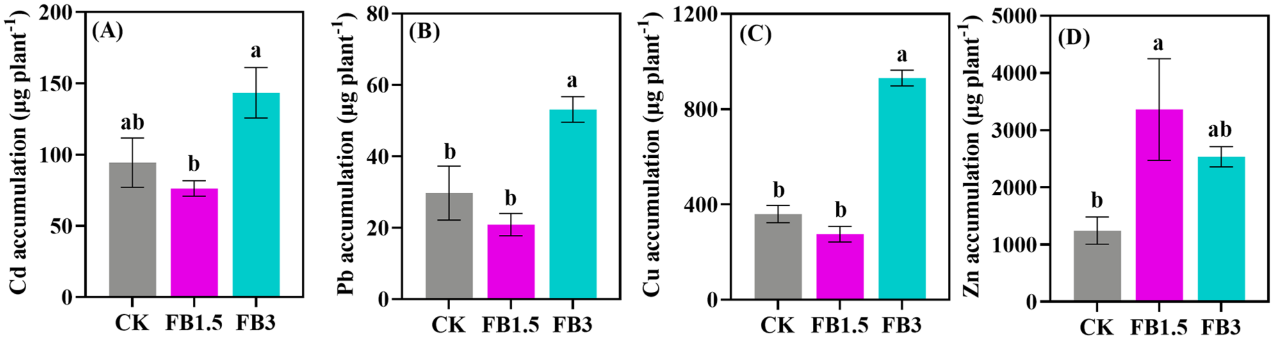
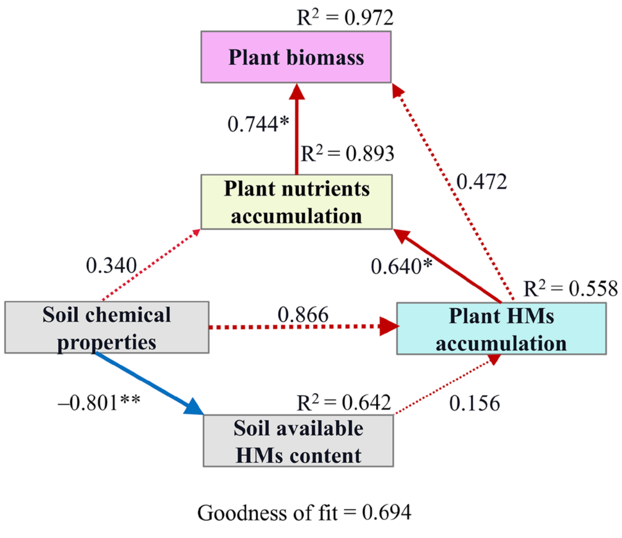


Figure 5. Effects of *Ficus altissima* litter-derived biochar (FB) at different rates i.e., 0, 1.5, and 3.0% (w/w, CK, FB1.5, and FB3), respectively, on plant Cd accumulation (A), plant Pb accumulation (B), plant Cu accumulation (C), and plant Zn accumulation (D) of *Monstera deliciosa* grown under sewage sludge amended soil. Values are mean ± standard error (n = 3). Different lowercase letters show significant differences between the means ($P < 0.05$)

2.4. The partial least squares path model

The partial least squares path model of FB application on soil chemical properties (soil organic matter, total N, total P, total K, available P, and available K), soil available HMs (Cu, Zn, Cd, and Pb) content, plant HMs (Cu, Zn, Cd, and Pb) accumulation, plant nutrients (N, P, and K) accumulation, and *M. deliciosa* biomass (dry weight) was shown in Figure 6. There was a high association between soil chemical properties and soil available HMs content ($P < 0.01$). Also, plant HMs accumulation was significantly and positively correlated with plant nutrients



Note: $^{**}P < 0.01$; $^{*}P < 0.05$. Numbers near the lines represent the standard path coefficients. R^2 indicates the variance of the dependent variable explained by the model. Solid red and blue arrows indicate positive and negative flows of causality ($P < 0.05$), respectively; dashed lines indicate non-significant ($P > 0.05$) pathways; arrow widths denote the magnitude of these effects.

Figure 6. The partial least squares path model of soil chemical properties (soil organic matter, total N, total P, total K, available P, and available K), soil available HMs (Cd, Zn, Pb, and Cu) content, plant HMs (Cd, Zn, Pb, and Cu) accumulation, plant nutrients (N, P, and K) accumulation, and biomass of *Monstera deliciosa* under the application rate of *Ficus altissima* litter-derived biochar (0, 1.5, and 3.0%)

accumulation ($P < 0.05$), and plant nutrients accumulation was significantly and positively correlated with plant biomass ($P < 0.05$). Application of FB at a higher rate, i.e., 3.0%, released more nutrient materials to the soil (Table 1) and promoted the nutrient uptake by *M. deliciosa* while increasing the adsorption capacity for HMs. Our study revealed that FB3 treatment promoted *M. deliciosa's* better ability of HMs and nutrients (N, P, and K) uptake.

3. Discussion

3.1. Effects of FB on soil properties and soil-plant heavy metals bioavailability

Biochar, with a large specific surface area and rich pore structure (Haider et al., 2021), can improve soil permeability and increase plant nutrient accumulation (Saluz et al., 2022; Sifton et al., 2022). Application of appropriate type and dosage of biochar can improve the physicochemical properties of soil, such as bulk density, capillary porosity, total porosity, capillary water capacity, pH, soil organic matter, total N, total P, total K, available P, and available K content (Shaaban et al., 2018), which may help to stabilize HMs in sewage sludge amended soil. In our study, after biochar addition, the sludge-amended soil was also analyzed for residual available heavy metal loads in different treatments before planting the *M. deliciosa* seedlings (Figure 2). Results demonstrated that FB3 treatment minimized soil available Pb, Cu, and Zn contents. This finding is consistent with previous results that HMs mobility were reduced after biochar addition (Pandey et al., 2022).

Several studies showed that biochar could adsorb and fix HMs in soil and reduce the proportion of exchangeable HMs in soil (Haider et al., 2021), thus achieving the effect of soil remediation and reducing the accumulation of HMs by plants (Jun et al., 2020; Pescatore et al., 2022). The HMs adsorption of biochar was related to plant HMs accumulation, but this effect varies according to the heavy metal species (Haider et al., 2022a, 2022b). In the present study, among all the treatments, FB3 treatment promoted plant growth, and HMs (Cd, Pb, Cu, and Zn) accumulation of *M. deliciosa*, and FB1.5 significantly promoted the Zn accumulation ($P < 0.05$), primarily owing to the application of FB have significant contribution to changing soil porosity and aggregate structure, regulating soil pH, and absorbing HMs in *M. deliciosa* from sewage sludge-amended soil (Gong et al., 2018; Irshad et al., 2020; Pandey et al., 2022). Besides, the plant Cd, Pb, and Cu accumulation were highest in FB3, indicating FB3 treatment had better HMs accumulation in *M. deliciosa* under sludge-amended soil (Mohamed et al., 2021).

3.2. Effects of FB on *M. deliciosa* growth and nutrients accumulation

Biochar improves the soil environment and increases the effectiveness of nutrients, promoting nutrient accumulation and plant utilization. the addition rate of biochar is related to plant nutrient accumulation, and excessive biochar addition may also absorb nutrients, such as C, N, and P, from the soil, creating a competitive effect with plants and inhibiting their growth (Teodoro et al., 2020; Xu et al., 2022). Therefore, in the application of biochar, CNP fertilizer can be applied with biochar to reduce the negative effects of biochar (Kononchuk et al., 2022).

In this experiment, we added sludge and biochar to the soil simultaneously, and the sludge is similar to a fertilizer that can provide nutrients for soil and plant. Results revealed that compared with CK, FB3 treatment promoted the root: shoot ratio of *M. deliciosa* and significantly increased its biomass. This is consistent with previous studies in which biochar stimulated the growth of zucchini (Farid et al., 2022). Also, FB1.5 significantly promoted the root: shoot ratio of *M. deliciosa* ($P < 0.05$). These results revealed that the application of biochar promoted nutrient accumulation of *M. deliciosa* under sludge-amended soil (Wu et al., 2022). Meanwhile, FB3 treatment significantly increased the N, P, and K accumulation of *M. deliciosa* ($P < 0.05$). This result may be due to the rich soluble mineral nutrients of sewage sludge and the sorption capacity of biochar, which increases the content of fast-acting nutrients in the soil and improves the utilization of plant nutrient accumulation (Ahmad et al., 2022).

3.3. Association between soil properties, plant nutrients accumulation, heavy metals bioavailability, and biomass

This study explores the relationship between soil physicochemical properties, soil HMs content, plant HMs accumulation, plant nutrient accumulation, and plant biomass. Our findings suggest that the soil pH likewise increased over control setups after applying FB (pH 12.53). Apart from that, the pH in sludge could also cause increased pH in substrates. Applying FB improved the pH and nutrient availability in sewage sludge-amended soil and positively influenced plant HMs uptake and biomass growth (Table 1, Figure 6).

Plant nutrients accumulation was positively associated with plant HMs accumulation. When amended with sludge, the soil pH improved compared with CK, which may enhance plant and biomass growth. Our findings revealed that adding biochar to sewage sludge amended soil improved HMs accumulation in plant tissue. Therefore, improving the physicochemical properties of the substrate is crucial for plant growth and nutrient accumulation. The *F. altissima* litter-derived biochar used in this study has a small pore size (average pore diameter = 34.7216 nm), and its adsorption capacity for HMs may be less than ideal. However, the garden waste biochar in our study was low in HMs but rich in nutrients and high in pH, suggesting that biochar can improve soil pH and be added to urban greening substrates as a fertilizer. In addition, using urban greening waste as biochar allows for waste utilization.

Table 1. Physicochemical properties in the sewage sludge-amended soil under *Ficus altissima* litter-derived biochar (FB) applied at rates of 0, 1.5, and 3.0% (w/w, CK, FB1.5, and FB3). Values are mean ± standard error (n = 3)

Paremeters	Treatments		
	CK	FB1.5	FB3
Bulk density (g cm^{-3})	$0.97±0.03^a$	$0.92±0.01^a$	$0.92±0.01^a$
Capillary capacity (g kg^{-1})	$528.78±26.16^a$	$564.11±98.94^a$	$640.2±35.69^a$
Total porosity (%)	$59.65±1.26^b$	$63.48±1.00^a$	$65.42±0.43^a$
Capillary porosity (%)	$56.41±1.94^a$	$54.08±8.00^a$	$58.67±3.42^a$
pH	$7.48±0.07^a$	$7.6±0.02^a$	$7.62±0.01^a$
Soil organic matter (g kg^{-1})	$67.43±6.70^a$	$80.48±2.62^a$	$79.94±6.86^a$
Total N (g kg^{-1})	$4.03±0.07^b$	$4.95±0.13^a$	$5.42±0.29^a$
Total P (g kg^{-1})	$2.60±0.04^b$	$2.98±0.07^a$	$3.07±0.03^a$
Total K (g kg^{-1})	$4.58±0.41^b$	$4.88±0.26^{ab}$	$5.63±0.02^a$
Available P (mg kg^{-1})	$313.13±17.23^b$	$385.29±11.18^a$	$364.80±6.27^a$
Available K (mg kg^{-1})	$239.25±6.29^c$	$523.35±15.18^b$	$819.93±8.12^a$

Note: N = nitrogen; P = phosphorous; K = potassium. Different lowercase letters show significant differences between the means ($P < 0.05$).

3.4. Prospects for biochar combined with landscape plant in soil remediation

Application of FB increased HMs bioavailability for *M. deliciosa*. A large amount of garden waste is produced yearly in urban greening in China. Disposal of garden waste is expensive while pyrolyzing garden waste into biochar is a low-cost disposal method (Hagenbo et al., 2022). Municipalities can collect, dispose of, and reuse garden waste, which helps to achieve carbon sequestration. Furthermore, built-up urban green spaces are still at risk of heavy metal contamination, and applying biochar prepared from waste to contaminated urban soils, combined with phytoremediation, can lead to comprehensive soil remediation (Kasak et al., 2018).

Compared to other heavy metal remediation methods (bioremediation and physical remediation), phytoremediation has irreplaceable advantages, such as being green and environmentally friendly and reducing the ecological risk of secondary pollution. Besides, phytoremediation can create an urban landscape and improve the green space environment. In the future, native plants with strong heavy metal bioavailability should be further screened. Meanwhile, plant selection criteria, configuration model, and plant landscape with multiple functions of ecological remediation should be established.

Conclusions

The addition of 3% biochar prepared from *F. altissima* litter in sewage sludge-amended soil resulted in significant improvements in substrate properties, growth of *M. deliciosa*, nutrient accumulation, and biomass. Notably, the plant's uptake of HMs (Pb and Cu) increased significantly after adding biochar. These findings highlight the potential of co-recycling sewage sludge and garden waste as a sustainable growing medium for landscape plants, facilitating the resourceful utilization of municipal waste. However, further research is required to determine the optimal biochar addition rate for sludge horticulture and to assess the long-term effects of the biochar aging process. This economically viable approach reduces waste management costs and contributes to long-term waste management strategies.

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Author contributions

Han Sheng: Formal analysis, Writing-original draft. Haider Fasih Ullah: Writing-review & editing. Weixin Peng: Investigation, Data curation. Jiayi Feng, Yuantong Yang, Xu Li, Fengling Long, Daoming Wu: Writing-review. Shucai Zeng: Writing-review & editing, Supervision, Funding acquisition.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ahmad, A., Chowdhary, P., Khan, N., Chaurasia, D., Varjani, S., Pandey, A., & Chaturvedi, P. (2022). Effect of sewage sludge biochar on the soil nutrient, microbial abundance, and plant biomass: A sustainable approach towards mitigation of solid waste. *Chemosphere*, *287*(Part 1), 132112. https://doi.org/10.1016/j.chemosphere.2021.132112

Alhar, M. A. M., Thompson, D. F., & Oliver, I. W. (2021). Mine spoil remediation via biochar addition to immobilise potentially toxic elements and promote plant growth for phytostabilisation. *Journal of Environmental Management*, *277*, 111500. https://doi.org/10.1016/j.jenvman.2020.111500

Álvarez, J. M., Pasian, C., Lal, R., López, R., Díaz, M. J., & Fernández, M. (2018). Morpho-physiological plant quality when biochar and vermicompost are used as growing media replacement in urban horticulture. *Urban Forestry* & *Urban Greening*, *34*, 175–180. https://doi.org/10.1016/j.ufug.2018.06.021

Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen–total. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis II*. American Society of Agronomy, Soil Science Society of America.

Chu, S., Jacobs, D. F., Liao, D., Liang, L. L., Wu, D., Chen, P., Lai, C., Zhong, F., & Zeng, S. (2018). Effects of landscape plant species and concentration of sewage sludge compost on plant growth, nutrient uptake, and heavy metal removal. *Environmental Science and Pollution Research*, *25*(35), 35184–35199. https://doi.org/10.1007/s11356-018-3416-x

Erdem, H. (2021). The effects of biochars produced in different pyrolsis temperatures from agricultural wastes on cadmium uptake of tobacco plant. *Saudi Journal of Biological Sciences*, *28*(7), 3965–3971. https://doi.org/10.1016/j.sjbs.2021.04.016

Farid, I. M., Siam, H. S., Abbas, M. H. H., Mohamed, I., Mahmoud, S. A., Tolba, M., Abbas, H. H., Yang, X., Antoniadis, V., Rinklebe, J., & Shaheen, S. M. (2022). Co-composted biochar derived from rice straw and sugarcane bagasse improved soil properties, carbon balance, and zucchini growth in a sandy soil: A trial for enhancing the health of low fertile arid soils. *Chemosphere*, *292*, 133389. https://doi.org/10.1016/j.chemosphere.2021.133389

Gong, X., Cai, L., Li, S., Chang, S. X., Sun, X., & An, Z. (2018). Bamboo biochar amendment improves the growth and reproduction of Eisenia fetida and the quality of green waste vermicompost. *Ecotoxicology and Environmental Safety*, *156*, 197–204. https://doi.org/10.1016/j.ecoenv.2018.03.023

Hagenbo, A., Anton-Fernandez, C., Bright, R. M., Rasse, D., & Astrup, R. (2022). Climate change mitigation potential of biochar from forestry residues under boreal condition. *Science of the Total Environment*, *807*(Part 3), 151044. https://doi.org/10.1016/j.scitotenv.2021.151044

Haider, F. U., Coulter, J. A., Cheema, S. A., Farooq, M., Wu, J., Zhang, R., Shuaijie, G., & Liqun, C. (2021). Co-application of biochar and microorganisms improves soybean performance and remediate cadmium-contaminated soil. *Ecotoxicology and Environmental Safety*, *214*, 112112. https://doi.org/10.1016/j.ecoenv.2021.112112

Haider, F. U., Farooq, M., Naveed, M., Cheema, S. A., Salim, M. A., Liqun, C., & Mustafa, A. (2022a). Influence of biochar and microorganism co-application on stabilization of cadmium (Cd) and improved maize growth in Cd-contaminated soil. *Frontiers in Plant Science*, *13*, 983830. https://doi.org/10.3389/fpls.2022.983830

Haider, F. U., Wang, X., Farooq, M., Hussain, S., Cheema, S. A., Ul Ain, N., Virk, A. L., Ejaz, M., Janyshova, U., & Liqun, C. (2022b). Biochar application for the remediation of trace metals in contaminated soils: Implications for stress tolerance and crop production. *Ecotoxicology and Environmental Safety*, *230*, 113165. https://doi.org/10.1016/j.ecoenv.2022.113165

Houssou, A. A., Jeyakumar, P., Niazi, N. K., Van Zwieten, L., Li, X., Huang, L., Wei, L., Zheng, X., Huang, Q., Huang, Y., Huang, X., Wang, H., Liu, Z., & Huang, Z. (2022). Biochar and soil properties limit the phytoavailability of lead and cadmium by Brassica chinensis L. in contaminated soils. *Biochar*, *4*(1), 5. https://doi.org/10.1007/s42773-021-00126-x

Ibrahim, E. A., El-Sherbini, M. A. A., & Selim, E.-M. M. (2022). Effects of biochar on soil properties, heavy metal availability and uptake, and growth of summer squash grown in metal-contaminated soil. *Scientia Horticulturae*, *30*, 111097. https://doi.org/10.1016/j.scienta.2022.111097

Irshad, M. K., Noman, A., Alhaithloul, H. A. S., Adeel, M., Rui, Y., Shah, T., Zhu, S., & Shang, J. (2020). Goethite-modified biochar ameliorates the growth of rice (*Oryza sativa* L.) plants by suppressing Cd and As-induced oxidative stress in Cd and As co-contaminated paddy soil. *Science of the Total Environment*, *717*, 137086. https://doi.org/10.1016/j.scitotenv.2020.137086

Jun, L., Wei, H., Aili, M., Juan, N., Hongyan, X., Jingsong, H., Yunhua, Z., & Cuiying, P. (2020). Effect of lychee biochar on the remediation of heavy metal-contaminated soil using sunflower: A field experiment. *Environmental Research*, *188*, 109886. https://doi.org/10.1016/j.envres.2020.109886

Kasak, K., Truu, J., Ostonen, I., Sarjas, J., Oopkaup, K., Paiste, P., Koiv-Vainik, M., Mander, U., & Truu, M. (2018). Biochar enhances plant growth and nutrient removal in horizontal subsurface flow constructed wetlands. *Science of the Total Environment*, *639*, 67–74. https://doi.org/10.1016/j.scitotenv.2018.05.146

Kononchuk, O., Pidlisnyuk, V., Mamirova, A., Khomenchuk, V., Herts, A., Grycová, B., Klemencová, K., Leštinský, P., & Shapoval, P. (2022). Evaluation of the impact of varied biochars produced from *M.* × giganteus waste and application rate on the soil properties and physiological parameters of *Spinacia oleracea* L. *Environmental Technology & Innovation*, *28*, 102898. https://doi.org/10.1016/j.eti.2022.102898

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, *14*(12), 883–892. https://doi.org/10.1038/s41561-021-00852-8

Liu, J., Jiang, L., Zhang, X., Fu, B., He, Z., Chen, M., Zeng, S., & Zhao, Q. (2023). Sewage sludge application stimulated soil N_2O emissions with a low heavy metal pollution risk in *Eucalyptus* plantations. *Journal of Environmental Management*, *339*, 117933. https://doi.org/10.1016/j.jenvman.2023.117933

Liu, K., Ran, Q., Li, F., Shaheen, S. M., Wang, H., Rinklebe, J., Liu, C., & Fang, L. (2022a). Carbon-based strategy enables sustainable remediation of paddy soils in harmony with carbon neutrality. *Carbon Research*, *1*(1), 12. https://doi.org/10.1007/s44246-022-00012-6

Liu, M., Ke, X., Liu, X., Fan, X., Xu, Y., Li, L., Solaiman, Z. M., & Pan, G. (2022b). The effects of biochar soil amendment on rice growth may vary greatly with rice genotypes. *Science of the Total Environment*, *810*, 152223. https://doi.org/10.1016/j.scitotenv.2021.152223

Liu, X., Ma, Y., Manevski, K., Andersen, M. N., Li, Y., Wei, Z., & Liu, F. (2022c). Biochar and alternate wetting-drying cycles improving rhizosphere soil nutrients availability and tobacco growth by altering root growth strategy in Ferralsol and Anthrosol. *Science of the Total Environment*, *806*(Part 1), 150513. https://doi.org/10.1016/j.scitotenv.2021.150513

Mohamed, B. A., Ellis, N., Kim, C. S., Bi, X., & Chen, W. H. (2021). Engineered biochars from catalytic microwave pyrolysis for reducing heavy metals phytotoxicity and increasing plant growth. *Chemosphere*, *271*, 129808. https://doi.org/10.1016/j.chemosphere.2021.129808

Pandey, B., Suthar, S., & Chand, N. (2022). Effect of biochar amendment on metal mobility, phytotoxicity, soil enzymes, and metal-uptakes by wheat (*Triticum aestivum*) in contaminated soils. *Chemosphere, 307*, 135889. https://doi.org/10.1016/j.chemosphere.2022.135889

Pescatore, A., Grassi, C., Rizzo, A. M., Orlandini, S., & Napoli, M. (2022). Effects of biochar on berseem clover (*Trifolium alexandrinum*, L.) growth and heavy metal (Cd, Cr, Cu, Ni, Pb, and Zn) accumulation. *Chemosphere*, *287*(Part 1), 131986. https://doi.org/10.1016/j.chemosphere.2021.131986

Pueyo, M., Mateu, J., Rigol, A., Vidal, M., López-Sánchez, J. F., & Rauret, G. (2008). Use of the modified BCR three-step sequential extraction procedure for the study of trace element dynamics in contaminated soils. *Environmental Pollution*, *152*(2), 330–341. https://doi.org/10.1016/j.envpol.2007.06.020

R Core Team. (2022). *R: A language and environment for statistical computing* (Version 4.2.1) [Computer software]. R Foundation for Statistical Computing.

Saluz, A. G., Bleuler, M., Krahenbuhl, N., & Schonborn, A. (2022). Quality and suitability of fecal biochar in structurally stable urban tree substrates. *Science of the Total Environment*, *838*(Part 3), 156236. https://doi.org/10.1016/j.scitotenv.2022.156236

Sarmah, M., Borgohain, A., Gogoi, B. B., Yeasin, M., Paul, R. K., Malakar, H., Handique, J. G., Saikia, J., Deka, D., Khare, P., & Karak, T. (2023). Insights into the effects of tea pruning litter biochar on major micronutrients (Cu, Mn, and Zn) pathway from soil to tea plant: An environmental armour. *Journal of Hazardous Materials*, *442*, 129970. https://doi.org/10.1016/j.jhazmat.2022.129970

Shaaban, M., Van Zwieten, L., Bashir, S., Younas, A., Núñez-Delgado, A., Chhajro, M. A., Kubar, K. A., Ali, U., Rana, M. S., Mehmood, M. A., & Hu, R. (2018). A concise review of biochar application to agricultural soils to improve soil conditions and fight pollution. *Journal of Environmental Management*, *228*, 429–440. https://doi.org/10.1016/j.jenvman.2018.09.006

Sifton, M. A., Lim, P., Smith, S. M., & Thomas, S. C. (2022). Interactive effects of biochar and N-fixing companion plants on growth and physiology of *Acer saccharinum*. *Urban Forestry & Urban Greening*, *74*, 127652. https://doi.org/10.1016/j.ufug.2022.127652

Teodoro, M., Trakal, L., Gallagher, B. N., Simek, P., Soudek, P., Pohorely, M., Beesley, L., Jacka, L., Kovar, M., Seyedsadr, S., & Mohan, D. (2020). Application of co-composted biochar significantly improved plant-growth relevant physical/chemical properties of a metal contaminated soil. *Chemosphere*, *242*, 125255. https://doi.org/10.1016/j.chemosphere.2019.125255

Tombarkiewicz, B., Antonkiewicz, J., Lis, M. W., Pawlak, K., Trela, M., Witkowicz, R., & Gorczyca, O. (2022). Chemical properties of the coffee grounds and poultry eggshells mixture in terms of soil improver. *Scientific Reports*, *12*, 2592. https://doi.org/10.1038/s41598-022-06569-x

Wu, D., Peng, W., Bao, L., Yu, X., Dong, X., Lai, M., Liang, Z., Xie, S., Jacobs, D. F., & Zeng, S. (2022). Biochar alleviating heavy metals phytotoxicity in sludge-amended soil varies with plant adaptability. *Environmental Research*, *215*, 114248. https://doi.org/10.1016/j.envres.2022.114248

Wu, D., Yu, X., Lai, M., Feng, J., Dong, X., Peng, W., Su, S., Zhang, X., Wan, L., Jacobs, D. F., & Zeng, S. (2021). Diversified effects of co-planting landscape plants on heavy metals pollution remediation in urban soil amended with sewage sludge. *Journal of Hazardous Materials*, *403*, 123855. https://doi.org/10.1016/j.jhazmat.2020.123855

Xu, Q., Song, X., Xu, M., Xu, Q., Liu, Q., Tang, C., Wang, X., Yin, W., & Wang, X. (2022). Elevated CO_2 and biochar differentially affect plant C:N:P stoichiometry and soil microbiota in the rhizosphere of white lupin (*Lupinus albus* L.). *Chemosphere*, *308*(Part 2), 136347. https://doi.org/10.1016/j.chemosphere.2022.136347

Yin, S., Zhang, X., Suo, F., You, X., Yuan, Y., Cheng, Y., Zhang, C., & Li, Y. (2022). Effect of biochar and hydrochar from cow manure and reed straw on lettuce growth in an acidified soil. *Chemosphere*, *298*, 134191. https://doi.org/10.1016/j.chemosphere.2022.134191

Yu, M., Liang, S., Dai, Z., Li, Y., Luo, Y., Tang, C., & Xu, J. (2021). Plant material and its biochar differ in their effects on nitrogen mineralization and nitrification in a subtropical forest soil. *Science of the Total Environment*, *763*, 143048. https://doi.org/10.1016/j.scitotenv.2020.143048

Zhang, X., Xie, H., Liu, X., Kong, D., Zhang, S., & Wang, C. (2021). A novel green substrate made by sludge digestate and its biochar: Plant growth and greenhouse emission. *Science of the Total Environment, 797*, 149194. https://doi.org/10.1016/j.scitotenv.2021.149194

Notations

Abbreviations

FB = *Ficus altissima* litter-derived biochar;
N = nitrogen;
P = phosphorous;
K = potassium;
AN = available nitrogen;
OP = olsen phosphorus;
HMs = heavy metals;
Cd = cadmium;
Pb = lead;
Cu = copper;
Zn = zinc.