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Tailored biochar for effective cadmium immobilization in soil and reduced accumulation in plants: a meta-analysis and experimental validation study

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Abstract

Soil available cadmium (Cd) governs its phytoavailability, thereby threatening food and medicinal plant safety. While biochar offers a promising remediation approach due to its high adsorption capacity and cost-effectiveness, its efficacy for Cd passivation requires a customized design. Here, a meta-analysis was conducted to examine how biochar preparation factors influence soil available Cd. The results indicate that biochar derived from herbaceous single Chinese medicine residues (SCMR), prepared at moderate-to-low pyrolysis temperatures (< 500 °C) with extended duration (> 3 h), achieved the highest Cd passivation efficiency. Adsorption kinetics experiments confirmed that biochar prepared from the decoction residue of *Houttuynia cordata* (i.e., a typical herbaceous SCMR) at 450 °C and 3.5 h exhibited optimal Cd adsorption capacity, verifying the meta-analysis. Pot experiments with lettuce (*Lactuca sativa* L.) further validated the findings of the meta-analysis: the 2% *H. cordata* biochar application led to the greatest reductions in soil available Cd and plant Cd accumulation by 17.6% and 52.3%, respectively. In heavy metal-accumulating medicinal plants (*Taraxacum officinale* F.H.Wigg. and *Lilium davidii* var. *willmottiae*), this biochar decreased soil available Cd by 18.0%–55.5% and plant Cd accumulation by 42.9%–68.6%. These results indicate the promising cross-species potential of the tailored biochar in mitigating Cd uptake in plants. In summary, this study establishes a meta-analysis-guided framework for tailoring biochar production, offers an evidence-based strategy for soil Cd remediation, and proposes a practical pathway for the valorization of Chinese medicine residues.

Highlights

- A comprehensive study guides biochar customization for soil cadmium passivation.
- Optimal biochar reduces soil available Cd by 55.5% and dandelion Cd by 68.6%.
- Our customized biochar is applicable for Cd uptake reduction in various plants.
- A promising yet underexplored route for valorization of Chinese medicine residues.

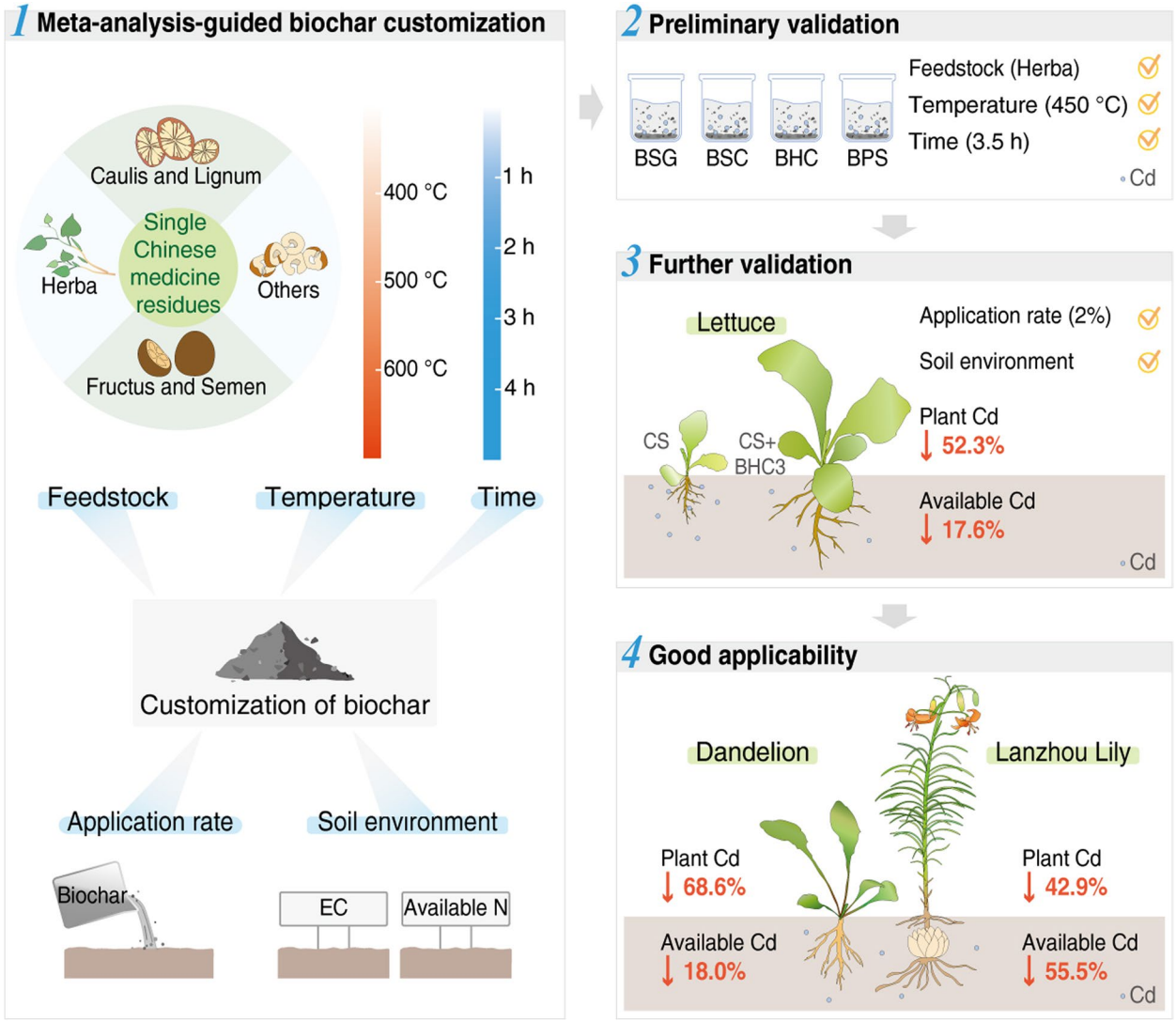
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Keywords Agricultural sustainability, Chinese medicine residues, Empirical research, Medicinal plants, Natural resource management, Pot experiment

Graphical Abstract



1 Introduction

Human activities such as mineral mining, misuse of chemical fertilizer, and sewage irrigation are the primary drivers behind the intensification and spread of heavy metal pollution in soil. As of 2025, approximately 16% of croplands worldwide are affected by toxic metal exceedances (Hou et al. 2025). Heavy metal contamination is also a major soil environmental issue in China, with cadmium (Cd) showing the highest exceedance rate at 7%. Accounting for 33.5% of all arable land pollution, Cd levels have continued to rise in recent years (Wen et al. 2022). The available metal concentrations in soils are strongly correlated with the heavy metal contents in plants, posing a direct threat to the food safety of edible plants (Zwolak et al. 2019). Therefore, it is imperative to reduce heavy metal accumulation in crops during soil cultivation. Biochar, produced by pyrolyzing biomass under oxygen-limited conditions, possesses a porous

structure, abundant surface functional groups, and high carbon content. It can improve soil physicochemical properties by regulating soil pH, reducing bulk density, and enhancing electrical conductivity (EC) and organic carbon content (Singh et al. 2022). Furthermore, its functional groups and negative charges can immobilize heavy metal ions directly or indirectly through complexation, precipitation, and ion exchange, effectively reducing their bioavailability (Duan et al. 2023). For instance, wheat plants grown in rice-husk biochar-amended soils showed approximately 32.9% and 41.0% reductions in Cd and Pb as compared with the control (Amin et al. 2023). However, the effectiveness and techno-economic feasibility of biochar in soil remediation depend on its physicochemical properties, which are largely determined by biomass feedstock and production methods.

The rapid expansion of the traditional Chinese medicine industry generates over 60 million tons of Chinese medicine residues (CMR) annually; however, current disposal methods such as incineration and landfilling contribute to environmental pollution and represent inefficient resource use (Deng et al. 2023). Rich in lignocellulose, CMR are increasingly being used as feedstock for biochar production in environmental remediation (Huang et al. 2025; Zhao et al. 2024). In particular, single Chinese medicine residues (SCMR) from traditional Chinese medicine formula granules production offer distinct advantages as feedstocks for the customized production of biochar compared to conventional lignocellulosic biomass. Their mineral-rich composition favors active adsorption site formation, while their naturally porous, high-lignin structure supports hierarchical pore development. Additionally, SCMR enables both waste valorization and predictable chemical tailoring due to its relatively homogeneous nature (Wu et al. 2025). For example, in terms of maximum adsorption capacities for tetracycline and methylene blue, those of an SCMR-based biochar were 1,516 mg/g and 1,034 mg/g, respectively (Guo et al. 2023; Shi et al. 2022), whereas those of a normal biomass-based biochar were only 76.7 mg/g and 31.1 mg/g, respectively (Zhang et al. 2023, 2024). In addition, the formula granules market has expanded substantially in recent years, growing consistently by 28% annually from 2.2 billion RMB in 2011 to 25.2 billion RMB in 2021 (Zhu et al. 2024). This growth has directly increased the generation of SCMR, providing ample feedstock for functionally enhanced biochar production.

While biochar has shown promise for heavy metal remediation in soil, its efficacy varies, with some studies reporting nonsignificant or even adverse effects on metal immobilization (Gascó et al. 2019; Yin et al. 2017). To optimize adsorption capacity, biochar must be tailored to specific pollutants and environmental conditions (Wei et al. 2023). Meta-analysis—a statistical synthesis of published data—can quantitatively evaluate effect sizes and variability across studies. This method, widely used in medical research to consolidate evidence (Kvam et al. 2016), can provide a rigorous framework for the systematic assessment of biochar performance. Currently, meta-analysis has increasingly been applied to guide environmental remediation; however, existing studies mainly focused on the overall effectiveness of biochar for heavy metal remediation, relying on broad parameter classifications or isolated discussions of individual preparation factors (Qie et al. 2023; Wei et al. 2024). All these findings generally lack experimental validation.

Compared with previous studies, this study systematically examines the key preparation parameters and investigates their interlinked effects on the physicochemical properties of biochar and its subsequent efficacy in Cd remediation. Shifting from macro-level integration to mechanism-targeted analysis, this work integrates data analysis with experimental validation to develop a novel pathway for functionally enhanced biochar. Specifically, this study aims to: (1) identify the optimal factors in preparing functional biochar for effective soil Cd remediation, including the SCMR type, pyrolysis temperature and time, and modification methods, based on studies selected for meta-analysis; (2) prepare biochar using SCMR for effective Cd passivation based on the optimal conditions identified through meta-analysis; (3) verify the efficacy of biochar in Cd adsorption kinetic study and lettuce cultivation experiments; and (4) test the applicability of biochar in experiments involving heavy metal-accumulating medicinal plants.

2 Materials and methods

2.1 Data compilation and normalization

The data used in this study were collected from the Web of Science database through a Boolean search using the following keywords: (biochar OR bio-char OR charcoal) AND (preparation OR modification OR properties) AND (heavy metal OR cadmium OR Cd) AND (stabilization OR immobilization OR passivation OR remediation OR pollution) AND (soil OR farmland OR arable land OR ground OR cultivated land). A total of 3,339 articles published between 2001 and 2024 were initially retrieved, among which 134 met the following selection criteria: (1) clear description of biochar preparation; (2) inclusion of pot or field plant cultivation experiments; (3) strict experimental design with biochar application as the sole variable; (4) measurement of key soil physicochemical properties (e.g., pH or Cd concentration) in both treatment and control groups; (5) at least three replicates per condition; and (6) presentation of original data as mean ± SD or mean ± SE (Fig. S1, Supplementary

Information). From these studies, 640 comparisons were extracted. A detailed list of the analyzed indicators is provided in Table S1.

WebPlotDigitizer (https://apps.automeris.io/wpd4/index.zh_CN.html) was used to digitize data from tables and figures in the included articles. The soil pH and organic matter indices were standardized, and the standard error (SE) values were converted to standard deviation (SD) values (Wei et al. 2023).

2.2 Meta-analysis

The effect of sample size for biochar application on the soil and plant parameters was calculated as the natural log-transformed response ratio (ln *RR*) using Eq. (1).

$$\ln RR = \ln \frac{X_t}{X_c} = \ln X_t - \ln X_c \tag{1}$$

where X_t indicates the mean value of the experimental groups, X_c indicates the mean value of the control groups (without biochar treatment).

The pooled variance (v) of the effect of sample sizes was calculated using Eq. (2).

$$v = \frac{S_t^2}{n_t X_t^2} + \frac{S_c^2}{n_c X_c^2} \tag{2}$$

where S_t and S_c are the standard deviations of the treatment and control groups, respectively, and n_t and n_c are the sample sizes of the treatment and control groups, respectively.

To account for the nested structure and non-independence of the observations, mixed-effects models were used to evaluate the effects of biochar application and changes in variables on Cd immobilization. The overall response effect was compared between the experimental and control groups by calculating the weighted mean response ratio ln(RR_{++}). Equations (4) and (5) were used to calculate the SE and 95% confidence interval (*95% CI*) of ln(RR_{++}), respectively.

$$\ln\left(RR_{++}\right) = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}(\ln RR)}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}} \tag{3}$$

$$s_{\ln\left(RR_{++}\right)} = \frac{1}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}} \tag{4}$$

$$95\%CI = \ln\left(RR_{++}\right) \pm 1.96 \times s_{\ln\left(RR_{++}\right)} \tag{5}$$

where m is the number of groups, k is the number of observations in the i-th group, i and j represent the i-th and j-th treatments, respectively. The weighting of each response ratio (w) is the reciprocal of its variance. If the 95% confidence interval does not overlap with zero, the biochar treatment effect is considered significant (Wei et al. 2024).

To explain this more clearly, ln(RR_{++}) and its *95% CI* were transformed as the percentage change using Eq. (6).

$$\textit{Percentage change}\ (\%) = \left[e^{ln(RR_{++})} - 1\right] \times 100\% \tag{6}$$

Publication bias assessment was conducted using Rosenberg's method (Table S2). If Rosenberg's fail-safe number is greater than 5n + 10, the dataset is considered reliable with no publication bias (Rosenberg 2005).

2.3 Customized biochar preparation

The four herbal residues selected in this study, *Sargentodoxa cuneata* ("caulis and lignum"), *Siraitia grosvenorii* ("fructus and semen"), *Houttuynia cordata* ("herba"), and *Paeonia suffruticosa* ("others"), were classified based on the texture of their medicinal parts. This classification could also correspond to common biochar feedstocks from forestry and agricultural residues (e.g., woody, straw/stalk, and shell/hull/peel biomass), providing guidance for biochar production from such lignocellulosic wastes. Meanwhile, all selected residues were from the commonly used traditional Chinese medicinal materials in the processing industry, and supplied by a leading local traditional Chinese medicine processing enterprise, where these herbs are routinely processed with stable and substantial outputs, ensuring a reliable supply for potential large-scale utilization. Using these residues as feedstocks, biochars were prepared by slow pyrolysis in an atmosphere furnace with a continuous flow of N_2 gas under different temperature and time settings (Table S3) as recommended by the meta-analysis.

The ash content of biochar was measured by pyrolyzing 0.5 g of biochar at 700 °C in a muffle furnace for 3 h. The C, H, and N contents in biochar were analyzed using an elemental analyzer (EA3000, Purkinje General Instrument Co., Ltd, Beijing, China). The biochar pH was determined using the potentiometric method. Biochar was ground and passed through a 60-mesh sieve before use.

Nitric and hydrochloric acids were bought from Shanghai Lingfeng Chemical Reagent Co., Ltd. and Dongguan Dongjiang Chemical Reagent Co., Ltd., respectively. All other chemicals used in this study were purchased from Aladdin (Shanghai, China) and Macklin (Shanghai, China) unless otherwise stated.

2.4 Adsorption kinetics

Adsorption kinetics of Cd^{2+} on biochars synthesized under varying conditions were investigated. In brief, 0.02 g of biochar was equilibrated with 10 mL of $CdCl_2$ solution (100 mg/L Cd^{2+}, pH 5) in a 15-mL centrifuge tube. The mixture was shaken at 160 rpm and 25 °C. Aliquots were taken at 0, 2, 4, 8, 12, 24, and 48 h, followed by centrifugation (4,000 rpm, 10 min) and filtration (0.45 μm). The Cd^{2+} concentration in the filtrate was quantified using atomic absorption spectrometry (AAS, TAS-990 AFG, Purkinje General, Beijing, China). The amount of Cd^{2+} adsorbed was calculated from the difference between the initial and equilibrium concentrations. Pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models were used to calculate the adsorption rate constants (Wang and Guo 2020), as follows:

$$Q_t = Q_e\left(1 - e^{-k_1 t}\right) \tag{7}$$

$$Q_t = \frac{k_2 t Q_e^2}{k_2 t Q_e + 1} \tag{8}$$

where t (h) is the adsorption time, Q_t ($mg{\cdot}g^{-1}$) is the adsorption capacity of biochar at t, Q_e ($mg{\cdot}g^{-1}$) is the adsorption capacity at adsorption equilibrium, and k_1 (h^{-1}) and k_2 ($g{\cdot}mg^{-1}{\cdot}h^{-1}$) are the PFO and PSO kinetic parameters, respectively.

2.5 Pot experiments

2.5.1 Soil preparation

The soil used in this study was collected from an abandoned farmland in Qinzhou, China (22.6126°N, 109.4568°E). Designated as "initial soil", it was acidic, reddish in color, and contained 0.74 mg/kg total Cd and 0.23 mg/kg available Cd. To obtain Cd-spiked soil, a $CdCl_2$ solution (9.23 mg/L) was added to the initial soil, raising the available Cd concentration to approximately 3.0 mg/kg (Kameyama et al. 2021). High-EC soil (1540 μS/cm) and high available-nitrogen soil (N-rich soil, 202.9 mg/kg) were subsequently prepared by adding NaCl solution and urea, respectively, to the Cd-spiked soil. All soils were air-dried and passed through a 10-mesh sieve before use. Detailed characteristics are provided in Table S4.

To investigate the effects of biochar feedstock on Cd remediation, biochar prepared from the SCMR of *Sargentodoxa cuneata*, *Houttuynia cordata*, *Siraitia grosvenorii*, or *Paeonia suffruticosa* (designated as BSC, BHC, BSG, or BPS, respectively) was amended into Cd-spiked soil at 2% (w/w). For dosage effects, BHC pyrolyzed at 450 °C for 3.5 h (hereafter, BHC3) was mixed with Cd-spiked soil at 1%, 2%, and 3%. Pots without biochar were set as the control group. To assess the influence of soil properties, BHC3 (2%) was mixed with high EC or N-rich soil. Unamended Cd-spiked soil was set as the control group. All treated soils were homogenized and stabilized for four weeks prior to potting.

2.5.2 Plant cultivation

The relationship between soil available Cd and plant Cd uptake was evaluated using three representative species: lettuce (*Lactuca sativa* L.), a model plant in phytoremediation, and two medicinal food plants noted for their strong heavy metal accumulation—dandelion (*Taraxacum officinale* F.H.Wigg.) and Lanzhou lily (*Lilium davidii* var. *willmottiae*). The experimental design is detailed in Table S5, with three replicates per treatment.

Lettuce, dandelion, and lily seeds (sourced locally) were germinated in peat-based seedling trays under moist conditions. Prior to the emergence of the third true leaf (lettuce) or at the 2–3 true leaf stage (dandelion), seedlings were transplanted into pots containing pre-treated soil. Lily bulbs were potted directly in soil and covered with cling film until germination. All plants were grown in a controlled environment chamber at 25 °C under a 12 h photoperiod, with approximately 80% relative humidity. Soil moisture was maintained at about 70% by watering every 2–3 days (lettuce and dandelion) or once weekly (lily). Unless otherwise specified, plants cultivated in Cd-spiked soil served as controls.

2.5.3 Sampling and analysis

Plants were harvested after 20 days (lettuce) or approximately 60 days (dandelion and lily) when significant differences from controls were observed. Harvested plant tissues were dried, ground, and digested with HNO_3 for Cd determination by AAS. Concurrently, collected soil samples were air-dried, sieved (2 mm), and analyzed for key properties: pH and EC were measured in soil–water suspensions (1:2.5 and 1:5, w/v) after equilibration, CEC was determined using the hexamine cobalt trichloride method (HJ 889–2017), and available Cd was extracted with DTPA (0.005 M, pH 7.3) and quantified by AAS according to GB/T 23739–2009.

2.6 Statistical analysis

All statistical analyses were performed using the R platform (version 4.4.1). The weighted mean response ratio, $\ln(RR_{++})$, was calculated using the R package *metafor*, and data were visualized using the R package *ggplot2* (Wei et al. 2023, 2024). All data were subjected to one-way analysis of variance and least significant difference

tests to compare the means. Differences were considered significant at p values less than 0.05.

3 Results and discussion

3.1 Meta-analysis-guided customized preparation of functional biochar

3.1.1 Feasibility of reducing soil available Cd and plant Cd accumulation

To assess the impact of biochar on soil Cd bioavailability and subsequent plant Cd accumulation, the overall responses of key indicators directly associated with Cd mobility were meta-analyzed. As shown in Fig. 1a, biochar application was found to alter soil properties, increasing the pH by 10.8% and decreasing the available Cd by 37.9%. When soil-available Cd was dominated by the acid-extractable fraction, its decline primarily resulted from the conversion of Acid-Cd (21.4%) to more stable Resid-Cd (31.7%) and Oxid-Cd (16.1%). Concurrently, the key soil physicochemical characteristics were modified, as indicated by increases in CEC and SOM of 23.9% and 48.6%, respectively. These increases likely enhanced Cd immobilization via cation exchange and complexation (Zhong et al. 2020), thereby reducing plant Cd accumulation by 41.1%. Interestingly, the application of biochar led to a 41.9% increase in plant biomass due to the reduced availability of heavy metals and improved soil conditions (Dai et al. 2020; Jindo et al. 2020).

After confirming the positive effects of biochar, a subgroup heterogeneity test was performed to assess how biochar preparation, properties, application, and soil conditions influence soil available Cd. Figure 1b shows significant heterogeneity in effect sizes ($p < 0.05$) across these parameters—including feedstock, pyrolysis conditions, modification, application rate, elemental composition (N/O), and soil properties (available N, EC)— indicating their key roles –indicating their key roles in determining biochar's efficacy for Cd immobilization.

3.1.2 Effects of biochar preparation and application rate on soil Cd immobilization

A comprehensive meta-analysis was conducted on key parameters: biochar feedstock type, pyrolysis conditions (temperature/duration), and modification methods. Significant variations ($p < 0.05$) in Cd immobilization efficacy were observed among these factors (Fig. 2a). Biochar derived from Fructus and Semen or Herba feedstocks demonstrated optimal Cd immobilization performance, reducing the soil available Cd by 36.8% and 35.0%, respectively. Feedstock type significantly affected biochar properties. Biochar derived from herbaceous biomass showed higher ash content, which correlated with increased pH and CEC. These properties enhanced

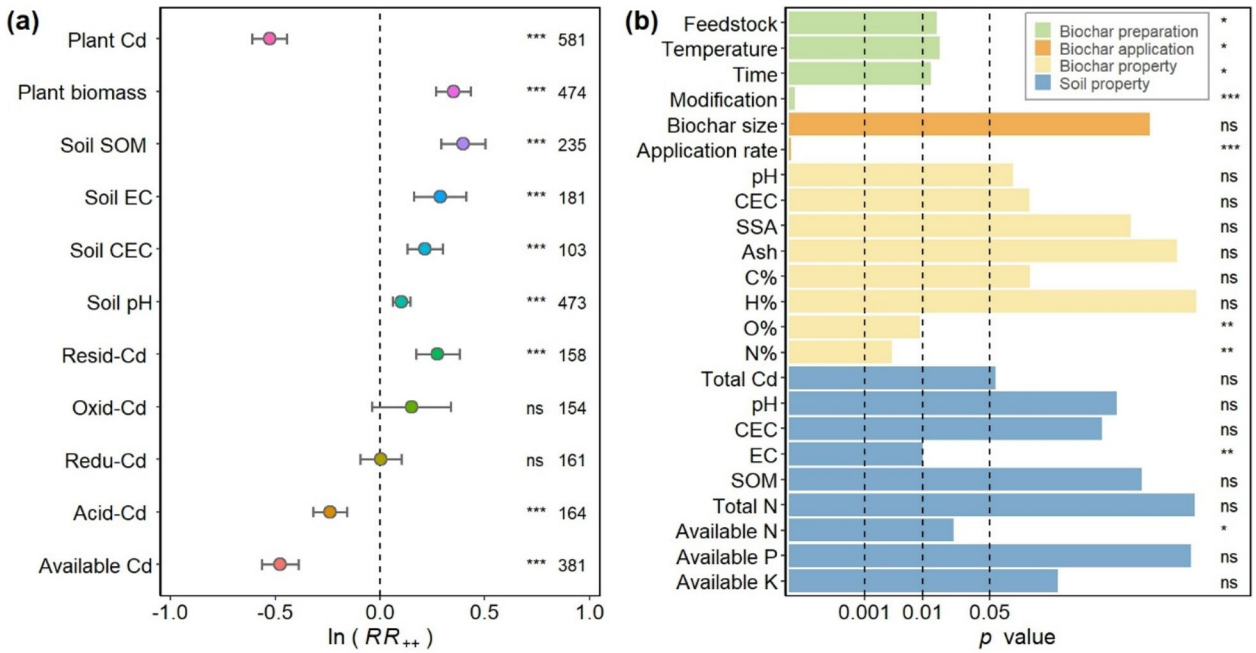


Fig. 1 **a** Overall effect of biochar application on critical soil and plant properties as determined through meta-analysis; **b** Effects of biochar preparation methods, properties, application methods, and soil properties on soil available Cd. Significance levels are indicated by * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$), and "ns" ($p > 0.05$); arabic numerals along the right side of the graph refer to the number of observations; error bars indicate 95% *CI*s

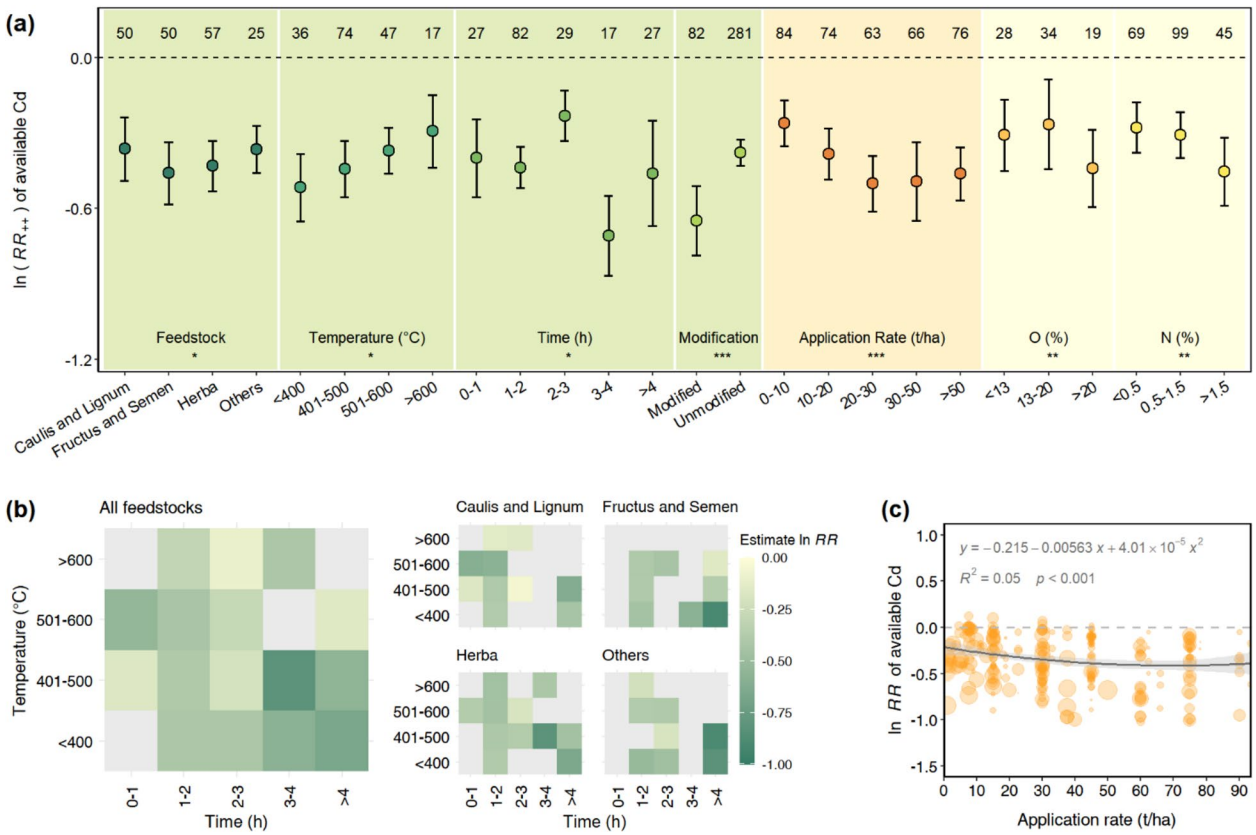


Fig. 2 Effects of biochar preparation and application rate on soil Cd immobilization as determined through meta-analysis. **a** Subgroup analysis; **b** Mixed-effects model analysis (grey squares indicate missing data); **c** Regression analysis of the effect of the application rate. Sampling variance is positively associated with the size of the data point; error bars and shaded areas indicate 95% *CI*s

Cd immobilization through surface complexation and precipitation mechanisms (El-Naggar et al. 2022; Singh et al. 2022). Notably, pyrolysis below 400 °C achieved maximum Cd immobilization (40.4%), while higher temperatures diminished this effect. Furthermore, a pyrolysis duration of 3–4 h enhanced Cd immobilization efficiency (50.7%) when compared with other treatment durations.

The mixed-effects model indicated that pyrolysis temperatures below 500 °C combined with durations longer than 3 h generally improved Cd immobilization (Fig. 2b, left panel). However, this thermal-temporal dependency was significantly influenced by feedstock type. Fructus- and Semen-derived biochars achieved optimum performance at lower temperatures (< 400 °C) with longer durations (> 4 h). Herba-derived biochar performed best under moderate conditions (401–500 °C, 3–4 h). In contrast, Caulis- and Lignum-derived biochars, characterized by higher lignocellulose content, required mid-range temperatures (401–500 °C) and extended pyrolysis (> 4 h) for maximum efficacy. These findings are consistent with previous reports that increasing pyrolysis temperature raises carbonization degree, pH, ash content, and EC in herbaceous biomass-derived biochars, and that longer duration enhances porosity (Cardenas-Aguiar et al. 2024). For lignum-based biochar, higher temperatures (450–500 °C) promote aromatic condensation and surface area development, and these features explain the distinct optimization window (Shaaban et al. 2014).

Subgroup analysis showed that biochar with high oxygen (O% > 20%) or nitrogen (N% > 1.5%) content led to the greatest reduction in soil available Cd (Fig. 2a). This result was supported by regression analysis (Fig. S4). These elemental features, which varied with feedstock and preparation conditions (Fig. 1b), correlated with Cd passivation efficacy. Nevertheless, directly targeting specific N or O content during production remains practically challenging and was therefore not experimentally validated in this study.

Building on the literature analysis (Fig. 1b), the current study assessed the effects of the biochar application rate on Cd immobilization in detail. As shown in Fig. 2a, increasing the application rate enhanced the reduction of soil available Cd, but this effect was minimized when the application rate exceeded 50 t/ha. Regression analysis

revealed a significant negative correlation between biochar application rate and soil available Cd ($R^2 = 0.05$, $p < 0.001$; Fig. 2c), indicating a quantifiable overall effect of application rate on Cd immobilization.

Chemical modification enhances biochar's capacity to immobilize heavy metals by altering its surface charge and functional groups (Figs. 1b and 2a). In our analysis (Fig. S3), biochars modified with acid, silicate, thiourea, and $KMnO_4$ reduced soil available Cd by 72.2%, 70.2%, 68.5%, and 58.2%, respectively. However, statistical robustness is limited due to small sample sizes ($n < 10$ for some modification methods).

3.1.3 *Influence of soil EC and soil available nitrogen*

Soil conditions can alter the efficacy of biochar for heavy metal immobilization (Chen et al. 2018; El-Naggar et al. 2022). The meta-analysis of existing literature revealed that soil available nitrogen and EC were important factors affecting the Cd immobilization by biochar (Fig. 1b). Biochar exhibited the greatest efficacy for immobilizing soil Cd (47.1%) when the soil EC was higher than 600 µS/cm. Similarly, when the available nitrogen content of soil was greater than 150 mg/kg, the soil available Cd was reduced by 50.2% (Fig. 3a). Further regression analysis revealed that the efficacy of biochar for available Cd immobilization exhibited a progressively increasing trend as the soil EC increased ($R^2 = 0.25$, $p < 0.001$) (Fig. 3b). Given the wide *95% CIs* observed in subgroups with soil available nitrogen levels greater than 150 mg/kg (Fig. 3a), we conducted a comprehensive regression analysis of the full dataset (Fig. 3b). The results demonstrated a unimodal relationship between the soil available nitrogen content (0–150 mg/kg) and the effectiveness of biochar in immobilizing available Cd ($R^2 = 0.28$, $p < 0.001$). This

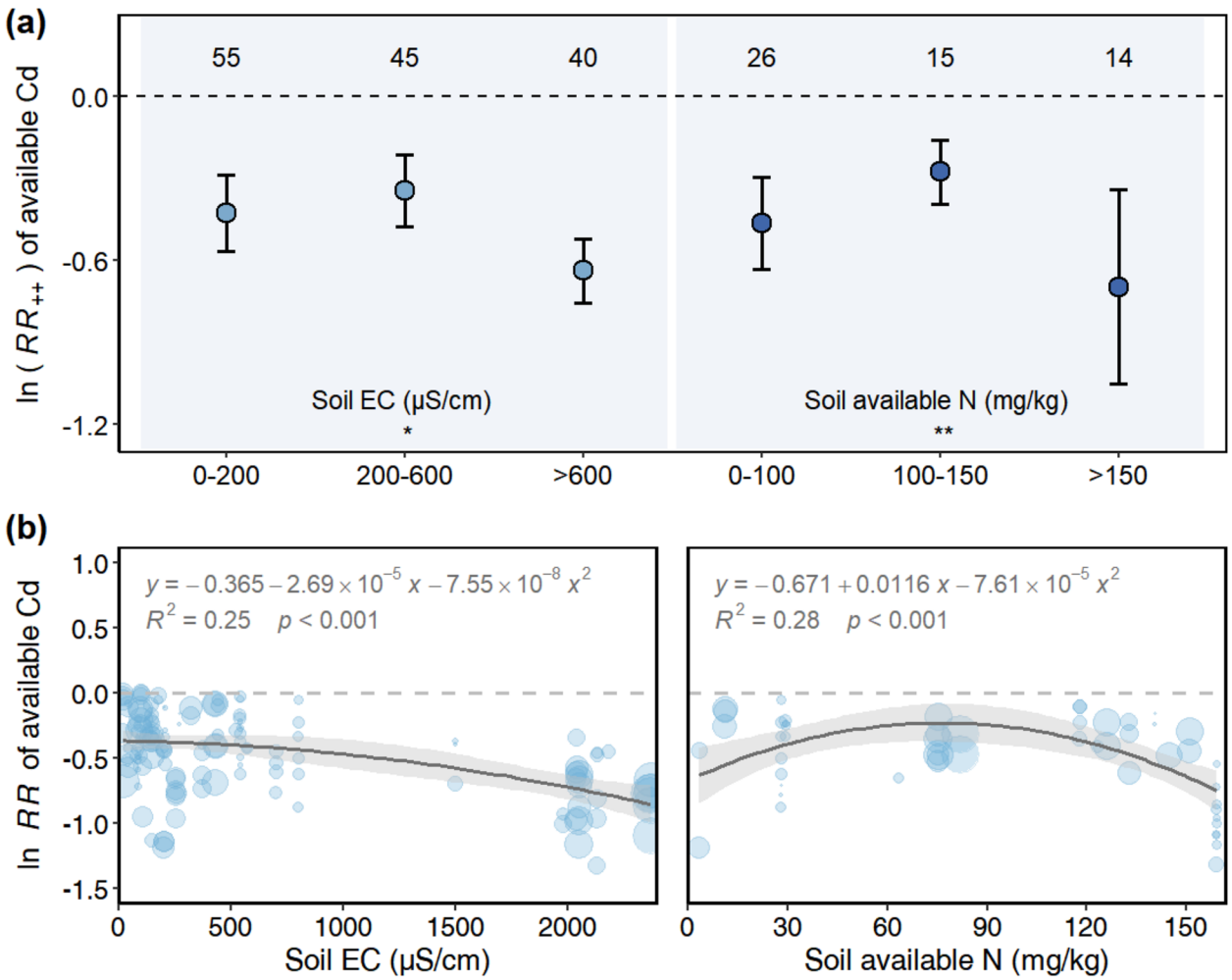


Fig. 3 Effects of soil EC and available nitrogen content on soil available Cd. **a** Subgroup analysis; **b** Regression analyses. Error bars and shaded areas indicate 95% *CI*s

pattern was consistent with the results of subgroup analysis (Fig. 3a).

3.2 Empirical validation of the results of meta-analysis

3.2.1 Preliminary validation through adsorption kinetics experiments

To validate the meta-analysis results (Figs. 1 and 2), solution-based kinetic experiments were conducted to compare the Cd^{2+} adsorption capacities of biochars from different feedstocks and pyrolysis conditions, serving as a comparative screening tool to identify optimal candidates for subsequent pot trials, rather than to simulate real-world soil conditions (Table S3). Based on the systematic analysis of Cd immobilization efficacy (Fig. 2b), preparation conditions yielding log response ratios (ln RR) < −0.75 were selected to optimize biochar production. To compare Cd immobilization performance across the four feedstock types, biochars were prepared under both their own optimal conditions (ln RR < −0.75) and the optimal conditions established for the other feedstocks (i.e., conditions yielding ln RR < −0.75). To ensure representative preparation conditions, we also included a high-temperature/short-duration protocol (550 °C, 1.5 h), as ln RR < −0.75 only occurred with low-temperature/long-duration conditions, and Caulis- and Lignum-derived materials showed ln $RR \geq -0.75$ across all tested conditions. This comparative approach allowed a comprehensive evaluation of Cd immobilization capacities across all preparation protocols.

As shown in Fig. 4, initially, Cd adsorption by all biochars increased rapidly, followed by a gradual approach to equilibrium over time. Generally, Herba-derived biochar (BHC) exhibited a much higher maximum Cd^{2+} adsorption capacity (29.5 mg/g) than other feedstocks—BPS (11.4 mg/g), BSC (8.2 mg/g), and BSG (1.5 mg/g)—consistent with the meta-analytical results and highlighting its superior Cd immobilization capability (Fig. 2a). Additionally, biochar produced under high-temperature/short-duration conditions (550 °C, 1.5 h) passivated the least Cd across all the feedstock types (Fig. 4). This indicates that high-temperature/short-duration pyrolysis is unfavorable for Cd immobilization, whereas biochar

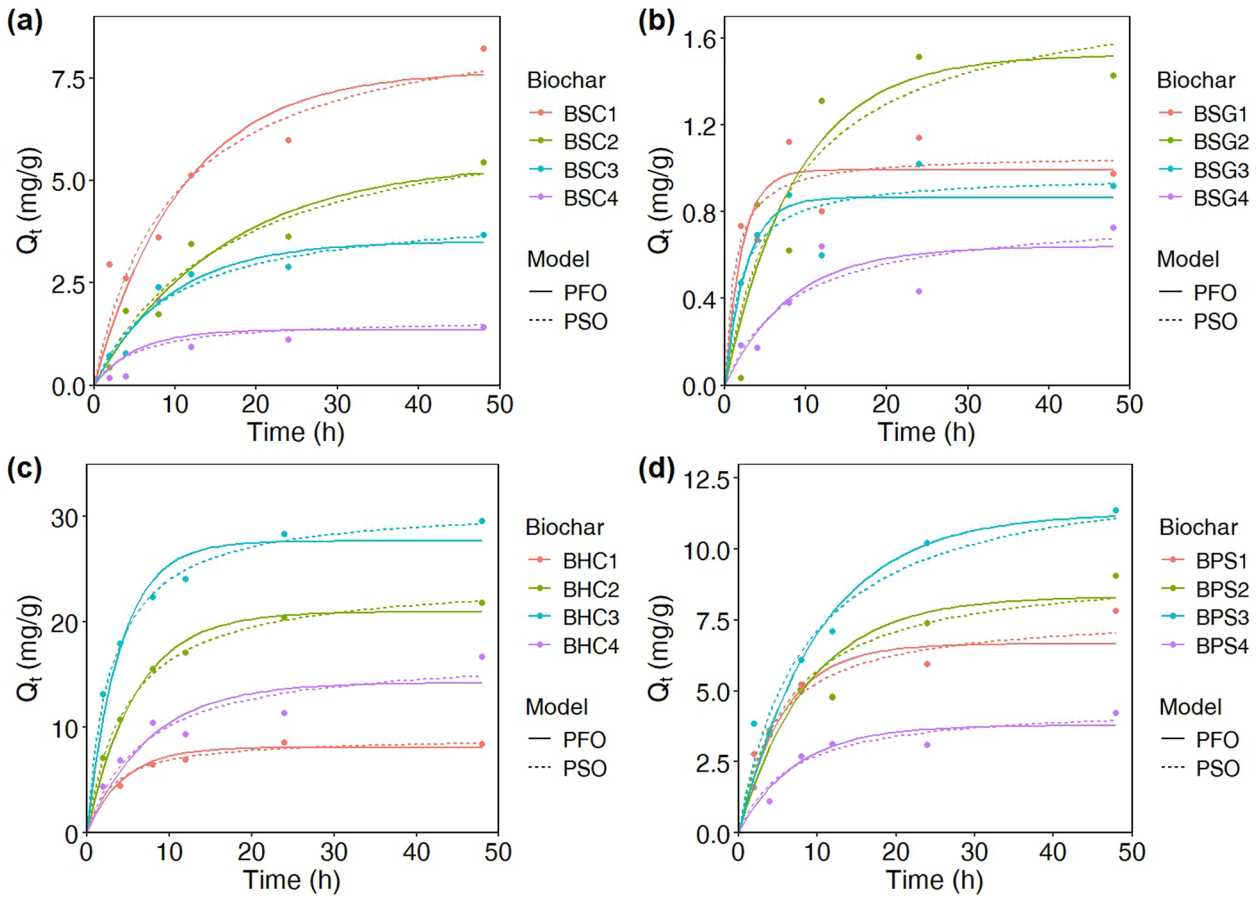


Fig. 4 Adsorption kinetics of biochars prepared using different feedstock and pyrolysis methods. **a** Biochar from *S. cuneata* residue (BSC); **b** Biochar from *S. grosvenorii* residue (BSG); **c** Biochar from *H. cordata* residue (BHC); **d** Biochar from *P. suffruticosa* residue (BPS)

Table 1 Kinetic parameters of BHC prepared under different pyrolysis conditions

	PFO model			PSO model		
	Q_e (mg·g^{-1})	k_1 (h^{-1})	R^2	Q_e (mg·g^{-1})	k_2 (g·mg^{-1}·h^{-1})	R^2
BHC1	8.105	0.229	0.984	9.013	0.036	0.972
BHC2	20.969	0.171	0.996	24.167	0.009	0.999
BHC3	27.681	0.253	0.982	31.125	0.011	0.997
BHC4	14.235	0.132	0.955	16.942	0.009	0.935

prepared at moderate-to-low pyrolysis temperatures for longer durations is conducive to Cd immobilization. These findings align with the general results of the meta-analysis (Fig. 2b, left panel).

Based on adsorption kinetics (Table 1), the adsorption data for BHC3 were better described by the PSO model than by the PFO model (R^2 = 0.997), indicating a chemisorption-dominated adsorption mechanism (Teng et al. 2020). Because chemisorption involves stable chemical bonding via ion exchange, surface complexation, or precipitation, Cd immobilization on BHC3 is expected to be more stable than on other materials. This also implied a greater quantity and/or variety of functional groups on the surface of BHC3 (Su et al. 2022). Biochars from *H. cordata* residues produced at low temperatures (BHC2 and BHC3) with extended pyrolysis likely possess abundant surface functional groups. This is because herbaceous biochars pyrolyzed below 500 °C tend to retain more functional groups (Janu et al. 2021). In comparison, lower-efficiency biochars (BHC4 and BHC1) conformed better with the PFO kinetic model, suggesting a physical adsorption-dominant mechanism where the adsorption process was rate-limited by diffusion steps (Qiu et al. 2023). Physical adsorption, which is achieved through physical interactions and characterized by poor stability, is strongly influenced by the pore structure and SSA of biochar (Gholizadeh and Hu 2021).

3.2.2 Further validation through pot experiments: biochar preparation and application

According to the results of meta-analysis and adsorption kinetics experiments, BSC2, BSG1, BHC3, and BPS2 were identified as biochars with the best Cd immobilization capability derived from their respective feedstocks. To further validate the meta-analytical results in practice (i.e., feedstock types, pyrolysis conditions, application rate), pot experiments involving biochar-treated, acidic Cd-spiked soil were conducted.

As shown in the upper panel of Fig. 5a, lettuce plants in the control group (without biochar application) exhibited stunted growth and pale, unhealthy leaves. In contrast, the biochar-treated lettuce plants demonstrated significant growth promotion, characterized by green, fully expanded leaves. Particularly, the BHC3 and BPS2 treatments exerted the most pronounced effects, producing robust plants with well-developed leaves. These results clearly indicate that the application of our biochar can enhance lettuce plant tolerance to both soil acidification and heavy metal stress (Amin et al. 2023; Zhang et al. 2020). Analysis of the soil available Cd content demonstrated that BHC3 and BPS2 reduced the soil available Cd content by 17.6% and 18.6%, respectively. Accordingly, a similar trend of Cd accumulation in lettuce was observed, with BHC3- and BPS2-treated groups exhibiting accumulation levels 52.3% and 54.0% lower, respectively, than that recorded in the control group. Studies have revealed that a high CEC or ash content in biochar can enhance the soil CEC and therefore facilitate Cd immobilization in contaminated soils (El-Naggar et al. 2022; Singh et al. 2022). We found that BHC3 (21.5%) and BPS2 (25.0%) exhibited higher ash contents than BSC2 (8.4%) and BSG1 (2.2%) (Table S6), which may have contributed to the superior Cd immobilization performance of BHC3 and BPS2 in pot experiments. Meanwhile, the disparity between the reduction (e.g., 17.6%) in available soil Cd and the decrease (e.g., 52.3%) in crop Cd accumulation highlights that the immobilization mechanism is not merely a proportional decrease in total labile pools, but rather a targeted attenuation of the rhizosphere bioavailability and root uptake efficiency. This amplified response may be owing to: (i) a significant reduction in the diffusion gradient of Cd^{2+} from the bulk soil to the root surface, governed by Fick's law, which exceeded the proportional decline in total extractable Cd (Zhang et al. 2025); and (ii) the possible formation of a physical/chemical barrier on root surfaces by the passivator particles (Xu et al. 2024). Furthermore, the concurrent increase in plant biomass (dilution effect) may have contributed to the higher magnitude of Cd reduction on a dry-weight basis.

As shown in Fig. 5b (upper panel), the growth status of lettuce exhibited a positive correlation with the application rate of biochar. As the biochar application rate increased from 1% to 3%, the plant height, leaf size, and coloration exhibited a progressive trend of improvement. Meanwhile, the soil available Cd decreased in a

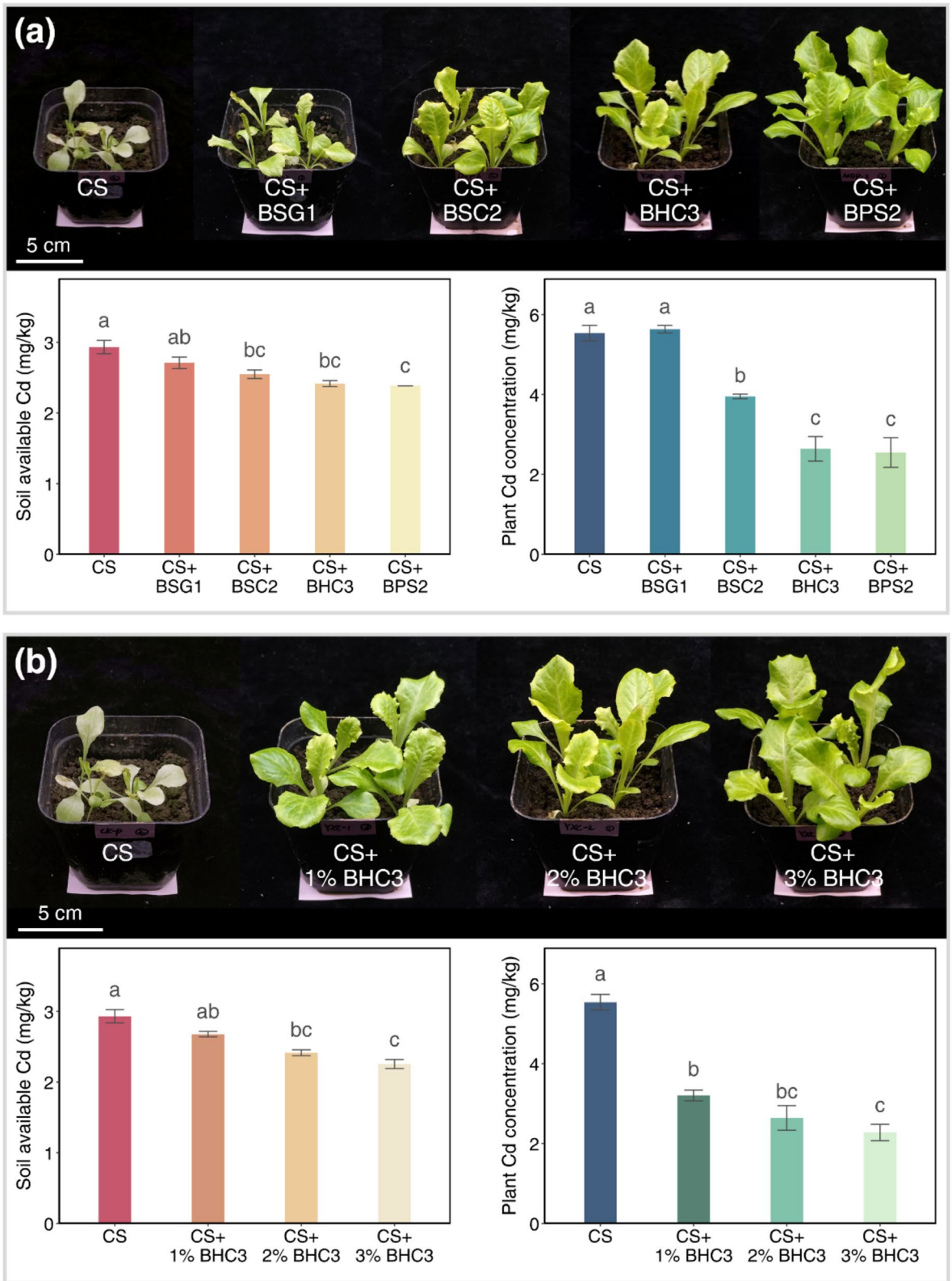


Fig. 5 Lettuce growth status, soil available Cd, and plant Cd concentration after cultivation for 20 days in a pot with biochar treatment. **a** Biochars prepared from different feedstock types under optimal conditions; **b** BHC3 at different application rates. Data are shown as mean ± SD; CS: Cd-spiked soil; "+": addition of biochar to the treatment

dose-dependent manner from 8.7% to 23.1%. Similar observations were made for the lettuce Cd content, as the Cd concentration in lettuce shoots decreased significantly by 42.1%–58.9%. However, no significant difference was observed in the effects of biochar on soil Cd immobilization or lettuce Cd reduction at application rates exceeding 2%. These results confirm the findings of our meta-analysis. To balance the cost and efficiency, 2% BHC3 was selected for subsequent pot experiments.

3.2.3 Further validation through pot experiments: soil EC and available nitrogen

Based on the meta-analytical results, the effects of soil EC and available nitrogen content on biochar-induced immobilization of soil available Cd by applying BHC3 to Cd-spiked, high EC, and N-rich soils were examined. Soils without treatment with BHC3 were set as the control groups (Fig. 6). Compared with the Cd-spiked soil, high EC and N-rich soils contained slightly higher levels of available Cd (Fig. 6a), indicating that either high EC or available nitrogen content could enhance Cd bioavailability in soils. These findings are consistent with previous

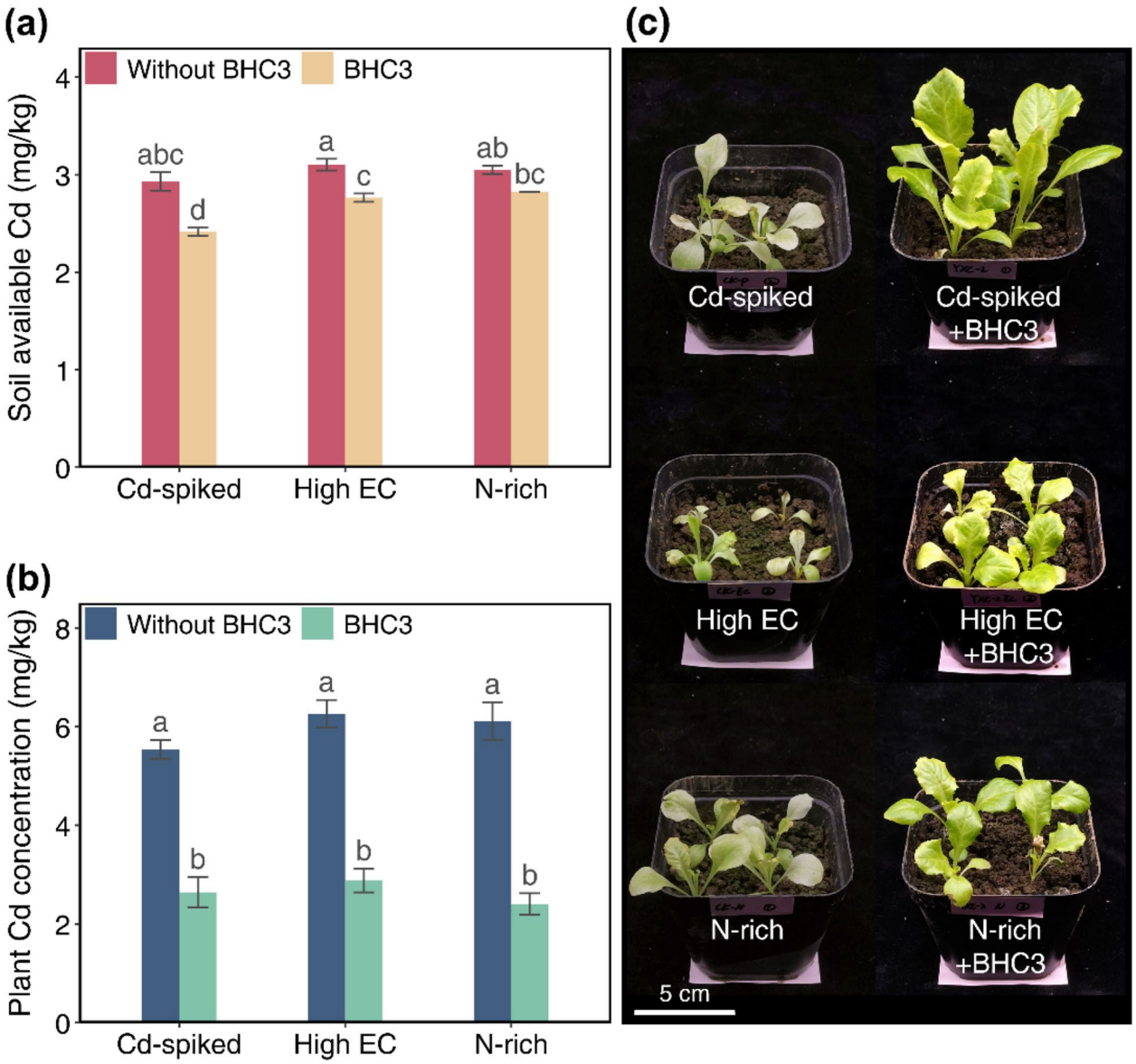


Fig. 6 Influence of soils with different physicochemical properties on Cd remediation. **a** Soil available Cd concentration; **b** Cd concentration in the above-ground parts of lettuce plants; **c** Lettuce growth status. Data are shown as mean ± SD; "+": addition of biochar to the treatment

analytical studies (Ata-Ul-Karim et al. 2020). However, BHC3 treatment effectively decreased the available Cd in all the soil samples, especially the Cd-spiked soil (17.6%). Regarding plant Cd accumulation (Fig. 6b), lettuces cultivated in high EC and N-rich soils had higher Cd contents (6.26 and 6.11 mg/kg) than those cultivated in Cd-spiked soil (5.54 mg/kg), which can be attributed to the lower available Cd in Cd-spiked soil. Following biochar application, Cd accumulation in lettuce cultivated in Cd-spiked, high EC, and N-rich soils decreased by 52.3%, 54.0%, and 60.7%, respectively. As a result, the growth of lettuce in soil not treated with biochar appeared to be suppressed by the heavy metal; this manifested as dwarfed plants with pale, poorly developed leaves. This suppressed growth phenomenon was more predominant in the high-EC soil, which had a higher soil available Cd. Although the application of biochar improved the growth conditions of all the lettuce plants, those planted in soils with higher EC and available nitrogen levels did not grow as well as those planted in the Cd-spiked soil.

3.3 Comparison with commercial biochar

To evaluate the practicality of customized biochar as prepared in this study, the efficacy of BHC3 on soil Cd remediation and plant Cd reduction was compared with that of a commercially available corn stover biochar (CBC, see Table S7 for its preparation method and characteristics). The Cd-spiked soil without addition of any biochar was set as the control group.

As shown in Fig. 7a, compared with lettuce cultivated in Cd-spiked soil, lettuce planted in soils amended with biochar had larger, greener leaves, and these effects were most pronounced in BHC3-treated plants. This result suggests that the customized biochar prepared in our study should be superior to a non-customized commercial biochar for remediating soil Cd pollution and preventing abiotic stress in plants, indicating the great potential for the use of SCMR in the customized preparation of biosorbents (Wu et al. 2025). Further investigation revealed that the application of BHC3 significantly increased the soil pH by 20.6% and CEC by 57.1%, while simultaneously reducing the available Cd content by 17.6%. In contrast, the commercial biochar significantly increased the soil EC, but it had no significant effect on the soil pH, CEC, or available Cd content (Fig. 7b–e). Correspondingly, the plant cultivated in soil treated with BHC3 exhibited superior growth compared with the control and commercial biochar groups (Fig. 7f–h). Specifically, lettuce cultivated in soil treated with BHC3 exhibited 60.1% and 15.9% higher growth than the control and commercial biochar groups, respectively. This effect was especially evident in plant fresh weight: lettuce grown in BHC3-amended soil yielded 4.5 times the biomass of the control group and 1.5 times that of lettuce grown in commercial biochar-amended soil. Consequently, BHC3 treatment demonstrated greater efficacy in reducing Cd accumulation in plants compared with the commercial biochar (i.e. 52.3% vs. 26.4%). The results demonstrate the superiority of BHC3 over corn stover-based commercial biochar for bioremediating soil heavy metal pollution.

3.4 Feasibility of applying BHC to other plants to reduce Cd accumulation

To investigate whether our biochar could reduce Cd accumulation in other plant species and to examine the relationship between soil available Cd and plant Cd uptake, dandelion and Lanzhou lily were selected as the research objects.

As shown in Fig. 8, BHC3 treatment clearly improved the growth conditions of both plants. Specifically, following the BHC3 application, the height and fresh weight of dandelion plants increased by 57.1% and 1.3 times, respectively. The soil pH increased by 39.8%, while the soil available Cd decreased by 18.0%. More importantly, the Cd concentration in dandelions grown in BHC3-treated soil decreased sharply from 11.3 to 3.5 mg/kg, a reduction of 68.6% (Fig. 8a). Similar effects were observed in Lanzhou lily plants (Fig. 8b). Following treatment with BHC3, the soil pH increased by 14.5% relative to the control group, while the soil available Cd decreased by 55.5%. Improvements in the lily plants were observed: while those grown in Cd-contaminated soil showed clear signs of toxicity, such as necrosis of the apical growth points, plants treated with biochar grew normally and completed the reproductive growth phase, reaching the flowering stage. The plant height increased significantly by 62.4%, the fresh weight of the medicinal/edible part (underground bulb) increased by 5.7%, and the Cd concentration decreased by 42.9%. These findings collectively demonstrate the robust efficacy of our biochar for mitigating heavy metal uptake across diverse plant species.

The experimental results reported in this study demonstrate that the optimized biochar based on meta-analysis has strong practical value for agricultural sustainability and further confirm the scientific value of our approach for guiding the development of biochar materials. However, it should be emphasized that while the 30-day equilibrated Cd-spiked soil used in this study ensures experimental reproducibility and effectively evaluates the immediate immobilization capacity of biochar for labile Cd species, this experimental design carries inherent limitations. Cd in artificially spiked soil exists predominantly in readily extractable forms such as the exchangeable fraction, which exhibits higher bioavailability compared to that in field-aged historically

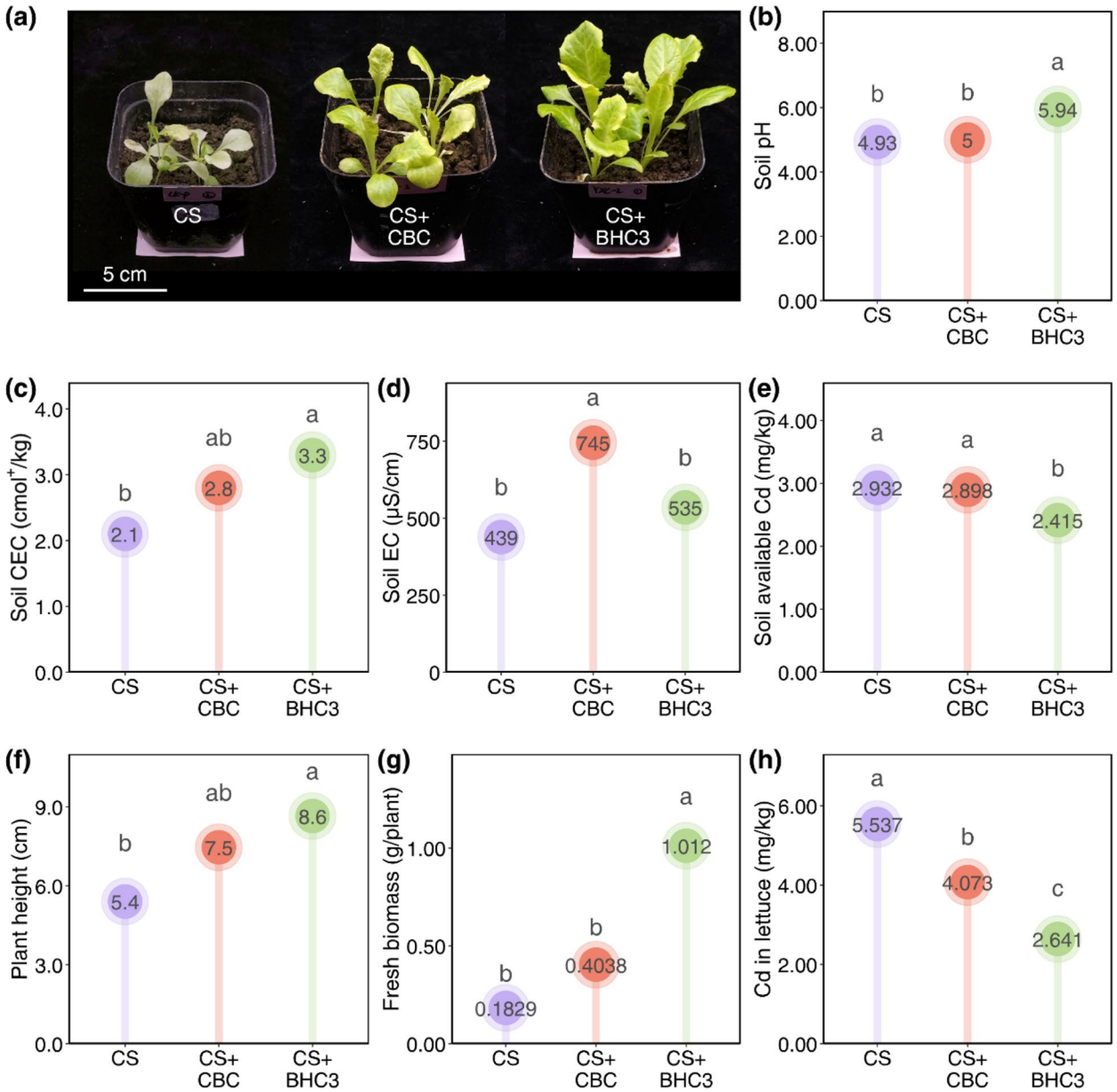


Fig. 7 Comparison of our biochar and a commercial biochar in terms of soil properties and plant growth. **a** Plant growth status; **b** Soil pH; **c** Soil CEC; **d** Soil EC; **e** Soil available Cd content; **f** Shoot height of lettuce; **g** Shoot fresh weight of lettuce; **h** Cd concentration in lettuce shoots. CS: Cd-spiked soil; "+": addition of biochar to the treatment

contaminated soils. This discrepancy suggests that the high Cd immobilization efficiency observed in this study may partially overestimate the actual remediation performance of biochar under complex field conditions. In actual contaminated sites, heavy metals undergo long-term interactions with soil components, leading to more stable speciation distributions. Moreover, spatiotemporal variations in soil physicochemical properties, dynamic environmental factors, and agricultural management practices may all influence the effectiveness and longevity of biochar-based remediation. Therefore, to more comprehensively assess the practical remediation potential of the biochar developed in this work, future studies should focus on its validation in multiple types of historically contaminated soils that vary in texture, pH, and contamination history, and then progressively advance to field-scale in situ trials.

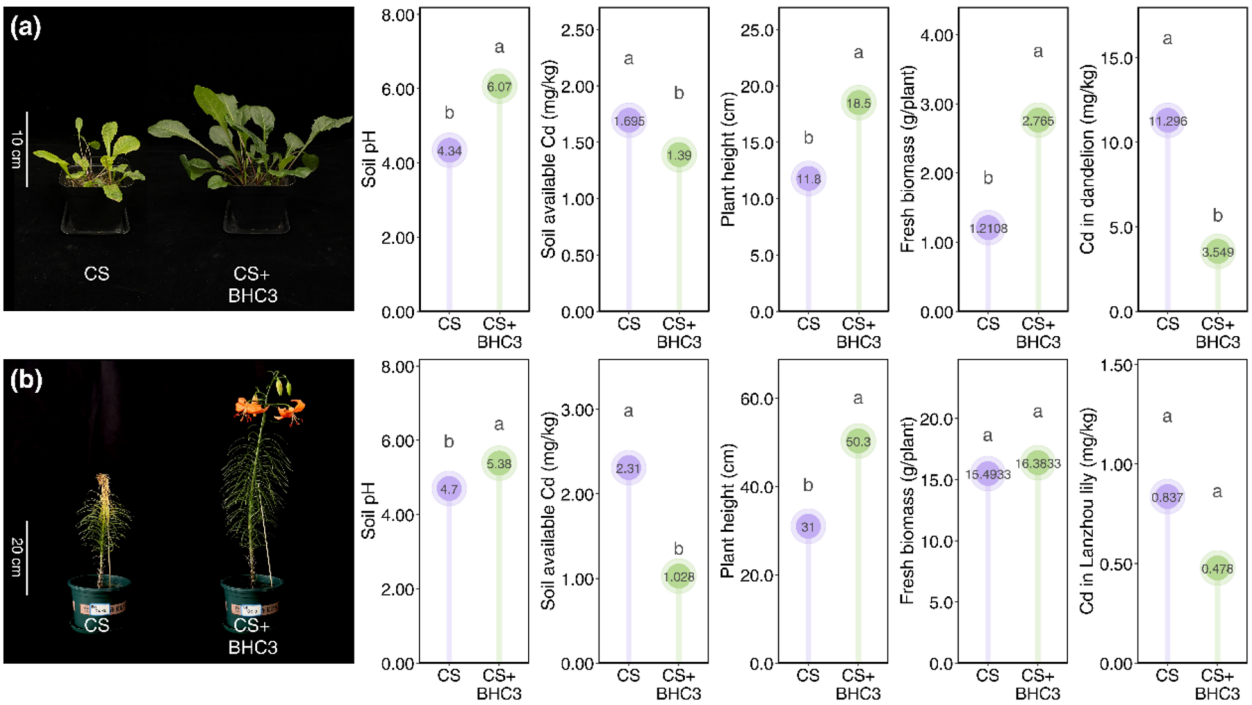


Fig. 8 Effects of biochar treatment on dandelion and Lanzhou lily growth in Cd-contaminated soil. **a** Dandelion; **b** Lanzhou lily. CS: Cd-spiked soil; "+": addition of 2% BHC3 to the treatment

4 Conclusions

This study proposes a pioneering meta-analysis-guided framework for the design and development of tailored biochar to enhance Cd immobilization in soil and reduce plant uptake. Optimal performance was achieved using herbaceous biochar produced at 401–500 °C for 3–4 h and applied at 2% (w/w), a formulation systematically identified and validated through integrated adsorption kinetics and plant growth experiments. Although further validation across a broader range of soil types and field conditions is necessary, the biochar developed in this study has demonstrated promising cross-species application potential in acidic Cd-contaminated pot trials. Overall, this work collectively suggests a promising yet underexplored pathway for designing functionally enhanced biochars.

Abbreviations

BHC	Biochar from *Houttuynia cordata* residue
BPS	Biochar from *Paeonia suffruticosa* residue
BSC	Biochar from *Sargentodoxa cuneata* residue
BSG	Biochar from *Siraitia grosvenorii* residue
CMR	Chinese medicine residues
SCMR	Single Chinese medicine residues

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44246-026-00302-3.

Supplementary Material 1

Authors' contributions

Xiaochen Zhu contributed to the methodology, data curation, formal analysis, writing – original draft, and visualization. Dai Dai, Beilei Wei, Yanan Yang, Jiawen He, Zhiyan Bai, Haixin Zheng, Weixiong Lin, and Zhenyao Wang contributed to the methodology, data curation, and resources. Hailong Wang contributed to writing – review and editing. Carol Sze Ki Lin and Ziting Wang contributed to project administration, writing – review and editing, and validation. Chong Li contributed to project administration, writing – review and editing, supervision, and funding acquisition. All authors read and approved the final manuscript.

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Data availability

Data will be made available on request.

Declarations

Competing interests

Hailong Wang is an Executive Editor-in-Chief of Carbon Research and was not involved in the editorial review of, or the decision to publish, this article. All authors declare that they have no other competing interests.

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