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Effect of Biochar Based Organic Fertilizer on Maize Growth in Cadmium Contaminated Soil

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Abstract

Soil heavy metal contamination, particularly by cadmium (Cd), poses a critical threat to global food security and public health. While biochar-based organic amendments represent a promising strategy for simultaneous soil remediation and crop promotion, optimizing fertilizer formulations to balance nutrient delivery with heavy metal immobilization remains a persistent challenge. Here, we evaluate the efficacy of various fertilization regimes—comprising standard organic fertilizers and two distinct biochar-based organic formulations (I and II) across three application rates (1500, 3000, and 4500 kg·ha^{-1})—on soil physicochemical properties, maize growth, and Cd sequestration. Our field experiments demonstrate that the maximum application of biochar-based organic fertilizer II (T9: 4500 kg·ha^{-1}) induced the most profound improvements in soil quality. Compared to the unfertilized control, T9 elevated soil pH by 0.69 units, organic matter by 43.661%, alkali-hydrolyzable nitrogen by 22.195%, and available potassium by 36.243%, ultimately culminating in a 64.078% increase in maize yield. Crucially, the 3000 kg·ha^{-1} treatments of both biochar-based fertilizers (T5 and T8) achieved identical maximum grain Cd reduction of 26.271%. Among them, T8 (modified biochar-based organic fertilizer II, 3000 kg·ha^{-1}) showed superior soil Cd immobilization capacity, decreasing DTPA-extractable soil Cd by 32.842% and outperforming conventional organic fertilizer and unmodified biochar-based organic fertilizer I. Collectively, customized biochar-organic composites can restore degraded contaminated soil while guaranteeing agricultural product safety, which provides a feasible and expandable technical scheme for low-carbon sustainable agriculture in heavy metal-polluted farmlands. The comprehensive performance of tested fertilizers followed the order: modified biochar-based organic fertilizer II > unmodified biochar-based organic fertilizer I > conventional organic fertilizer. Notably, optimal dosages diverged for Cd remediation (3000 kg·ha^{-1}, T8) and grain yield promotion (4500 kg·ha^{-1}, T9), owing to distinct limiting factors of heavy metal immobilization and crop nutrient demand.

Keywords

Biochar Based Organic Fertilizer, Corn, Cadmium, Repair, Grow

1. Introduction

The rapid intensification of industrial and agricultural activities has exacerbated soil heavy metal contamination, posing a severe global environmental challenge. These pollutants are readily absorbed by crops and enter the food chain, presenting substantial risks to human health (Li et al., 2025a). Chronic exposure to heavy metals, particularly cadmium, is well-documented to cause nephrotoxicity, cardiovascular damage, oncogenesis, and functional impairment of the digestive and hematopoietic systems (Åkesson et al., 2014). To mitigate these risks, developing efficient, eco-friendly, and low-carbon remediation technologies is critical for sustainable soil management. Among various strategies, biochar has emerged as an exceptionally promising amendment. Its porous architecture and rich surface functional groups—including hydroxyl, olefin, and organic oxygen groups—stabilize heavy metals, improve soil physicochemical properties, and enhance fertility, thereby fostering optimal plant growth.

Building on these advantageous properties, substantial research has explored the application of biochar and its derivatives in remediating heavy metal-contaminated soils. For instance, Wei et al. (2023) demonstrated that biochar effectively immobilizes cadmium and elevates soil pH, yielding significant remediation outcomes. To further enhance this efficacy, structural and chemical modifications have been investigated; Li and Chen (2023) observed that iron-modified biochar exhibits superior performance in promoting maize growth and immobilizing heavy metals compared to pristine biochar. Additionally, Huang et al. (2019) verified that the co-application of biochar-based organic fertilizers with mushroom residue wood vinegar significantly reduces the concentration and bioavailability of exchangeable copper. Collectively, these studies underscore the immense potential of biochar-based fertilizers in agricultural soil remediation.

However, despite these promising findings, current research is predominantly confined to short-term pot experiments. A significant knowledge gap remains regarding the practical efficacy of biochar-based organic fertilizers under actual field conditions. Specifically, the long-term impacts of these amendments on field crop development, alongside the *in situ* dynamics of heavy metal uptake and accumulation, remain inadequately explored.

To bridge this knowledge gap, this study utilized corn straw as a sustainable feedstock to synthesize a chemically modified biochar, which was subsequently integrated with conventional organic fertilizers to formulate a novel biochar-based organic fertilizer. Through comprehensive field trials, we systematically investigated the effects of varying application rates on soil nutrient availability, the suppression of cadmium translocation in maize, and overall crop productivity. Ultimately, this research aims to provide precise, evidence-based guidelines for the practical application of biochar-based fertilizers, offering a robust technical framework to advance field-scale soil remediation and low-carbon agricultural practices.

2. Materials and Methods

2.1. Test Time and Location

Field trials were implemented from May to November 2024 at Luoyizhai, adjacent to the G5615 Tianhou Expressway in Gejiu City, Honghe Hani and Yi Autonomous Prefecture, Yunnan Province, China. The test site belongs to the subtropical plateau monsoon climate zone, with elevations of 1500 - 1900 m, annual average temperatures of 18˚C - 24˚C annual rainfall of roughly 800 mm, and total annual sunshine hours of approximately 2200 h. The local frost-free period exceeds 300 days. Long-term lead and tin mining activities have caused severe Cd pollution in local farmland. The experimental soil is classified as red earth, with baseline physicochemical properties as follows: pH = 6.46, alkaline-hydrolyzable nitrogen = 154.215 $mg \cdot kg^{-1}$, soil organic matter = 22.25 $g \cdot kg^{-1}$, available phosphorus = 27.89 $mg \cdot kg^{-1}$, total Cd = 2.84 $mg \cdot kg^{-1}$, available potassium = 449.76 $mg \cdot kg^{-1}$. In accordance with the national standard GB 15618-2018 *Soil Environmental Quality—Risk Control Standard for Agricultural Land Contamination*, the Cd concentration of the test soil exceeds the pollution risk threshold for farmland with pH ranging from 5.5 to 6.5, which confirms serious Cd pollution at the experimental site.

2.2. Experimental Materials

2.2.1. Preparation of Biochar

Raw biochar was manufactured from local maize straw at the Yunnan Provincial Engineering Research Center for Soil Fertility and Pollution Remediation. Briefly, air-dried straw was pulverized and sieved through a 100-mesh screen. Straw powder underwent oxygen-limited pyrolysis in a tube furnace at 500˚C for 2 h under continuous N_2 purging. Cooled raw biochar was sealed in wide-mouth glass containers and stored under dry ambient conditions for subsequent modification and compound fertilizer blending.

2.2.2. Preparation of Potassium Permanganate Modified Biochar

$KMnO_4$-functionalized biochar was prepared following the protocol described by Mo et al. (2021). A total of 2.0 g raw straw biochar was transferred into a 250 mL Erlenmeyer flask and mixed with 100 mL 0.1 $mol \cdot L^{-1}$ $KMnO_4$ aqueous solution. The sealed flask was incubated in a thermostatted shaker at 25˚C with shaking speed set to 200 rpm for 6 h. After static sedimentation for 1 h, the suspension was vacuum-filtered, and solid residues were repeatedly rinsed with deionized water until eluates turned transparent. Recovered modified biochar was oven-dried at 75˚C to constant mass before use.

2.2.3. Characterization of Biochar

Brunauer-Emmett-Teller (BET) nitrogen adsorption measurements were conducted to quantify biochar specific surface area and pore size distribution. Scanning electron microscopy coupled with energy-dispersive X-ray elemental mapping (SEM-EDS mapping) was used to observe surface micro-morphology and elemental distribution (Jiang et al., 2024).

2.2.4. Test Material

The local maize cultivar Xuanhong 99, purchased from a regional agricultural supply store, was planted across all experimental plots. Two biochar compound organic fertilizers were formulated with a fixed biochar-to-manure mass ratio of 1:4: Fertilizer I blended unmodified straw biochar with commercial manure fertilizer (2.19% N, 1.23% P, 2.21% K); Fertilizer II used $KMnO_4$-modified biochar as the carbon component (2.13% N, 1.29% P, 2.30% K). Both compound fertilizers complied with agricultural industry standard NY/T 3618-2020. The base commercial organic fertilizer was supplied by Yunnan Nongjiale Agriculture Group Co., Ltd., consisting of fermented chicken and sheep manure with total N-P-K concentrations of 1.99%, 1.38%, and 2.12%, respectively. The basic properties of the tested materials are shown in **Table 1**.

Table 1. Properties of tested materials.

Index	pH	Organic matter (g/kg)
Biochar	8.73	620.26
Modified biochar	8.35	608.13
Organic fertilizer	7.56	512.48

2.3. Experimental Design

A randomized complete block design (RCBD) was used in this field trial, which consisted of 10 fertilization treatments with three biological replicates per treatment, yielding 30 independent 20 m^2 experimental plots (**Table 2**). A 1.0 m wide unfertilized buffer zone was arranged between neighboring plots to limit lateral water infiltration and cross-plot migration of macronutrients. All fertilizers were applied as basal amendments prior to maize sowing. Each fertilizer was evenly spread across the plot surface and fully mixed into the 0 - 20 cm topsoil via rotary tillage, followed by plastic film mulching and seed sowing; no supplementary top-dressing was applied during the entire growing season. Consistent agronomic practices, including irrigation, pest control and weeding, were implemented uniformly for all plots, with fertilizer type and application rate set as the exclusive experimental variables. Note that total N, P, K nutrient inputs differed among treatments with varying fertilizer types and application rates, which may interfere with the comparison of pure biochar modification effects.

Table 2. Experimental design.

Treatment	Code	Application rate (kg·ha^{-1})
Contrast	CK	0
Organic fertilizer	T1	1500
	T2	3000
	T3	4500
Biochar based organic fertilizer I	T4	1500
	T5	3000
	T6	4500
Biochar based organic fertilizer II	T7	1500
	T8	3000
	T9	4500

Note: blank control (CK), 1500 kg·ha^{-1} (T1), 3000 kg·ha^{-1} (T2), 4500 kg·ha^{-1} (T3), 1500 kg·ha^{-1} (T4), 3000 kg·ha^{-1} (T5), 4500 kg·ha^{-1} (T6), 1500 kg·ha^{-1} (T7), 3000 kg·ha^{-1} (T8), 4500 kg·ha^{-1} (T8) and 4500 kg·ha^{-1} (T5), respectively kg·ha^{-1} (T9); There was significant difference in the expression of different letters ($P < 0.05$).

2.4. Sample Collection and Determination Analysis

At maize physiological maturity, five representative plants per plot were collected via five-point sampling to measure vegetative indices and grain yield. Plant height was measured vertically from soil surface to the apex of the primary ear using a tape measure. Canopy width was determined by caliper measurement of the widest fully expanded leaf, with calipers held parallel to the leaf lamina. Functional leaf length was recorded from leaf base to leaf tip with a graduated ruler. Harvested plants were air-dried and threshed to calculate plot grain yield. Only maize kernels were retained for Cd quantification: kernels were sequentially rinsed with tap water and ultrapure water, deactivated at 105˚C for 30 min, then oven-dried at 65˚C to constant mass. Dried grain samples were pulverized and sieved for elemental digestion. Composite topsoil (0 - 20 cm) samples were collected at two time points (pre-sowing and maize maturity) using five-point sampling (Liu et al., 2024). Air-dried soil samples were ground and sequentially sieved through 2 mm, 1 mm, and 0.149 mm meshes before sealed storage for physicochemical and Cd analysis.

All soil physicochemical indices were measured following standard agrochemical analytical protocols. Plant-available soil Cd was extracted with DTPA solution per GB/T 3739-2009 and quantified via atomic fluorescence spectrometry. Maize grain Cd concentrations were determined by atomic absorption spectrophotometry after microwave-assisted nitric acid digestion, complying with food safety standard GB 5009.15-2014. The measured Cd concentrations in maize grains were subsequently compared against the maximum permitted limit for contaminants in foods (0.1 mg/kg for cereals, strictly adhering to China's National Food Safety Standard GB 2762-2022) to evaluate the practical crop safety. Soil pH was measured using a calibrated digital pH meter in soil-water suspensions (soil:water = 1:2.5).

2.5. Statistical Analysis

Raw data collation and preliminary calculation were completed in Microsoft Excel 2016. Descriptive statistics (mean ± standard deviation) and significance testing were performed in SPSS Statistics 26. Inter-treatment mean differences were separated via Duncan's multiple range test at $P < 0.05$. All experimental figures were visualized using Origin 2021.

3. Results and Analysis

3.1. Surface Morphology Analysis of Biochar (SEM Mapping)

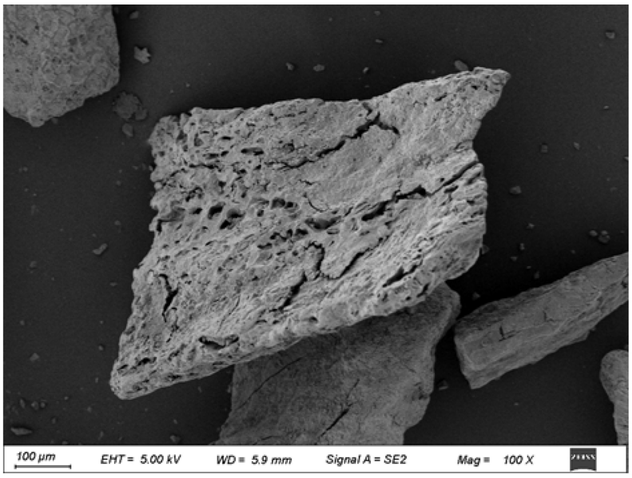
Figure 1 presents SEM micrographs of unmodified straw biochar and $KMnO_4$-modified biochar captured at 100× and 1000× magnification. Raw biochar exhibited smooth, compact surfaces with sparse pore structures. In contrast, oxidative $KMnO_4$ modification induced severe surface fragmentation and abundant new pore cavities, alongside scattered mineral fine particles precipitated across the biochar matrix; these structural alterations collectively enlarge material specific surface area.

SEM-EDS elemental mapping (Figure 2) revealed distinct disparities in surface C, N, O, P, and Mn elemental abundances between the two biochar variants. Manganese species were uniformly deposited onto modified biochar surfaces after $KMnO_4$ treatment, verifying successful Mn functionalization of straw biochar.

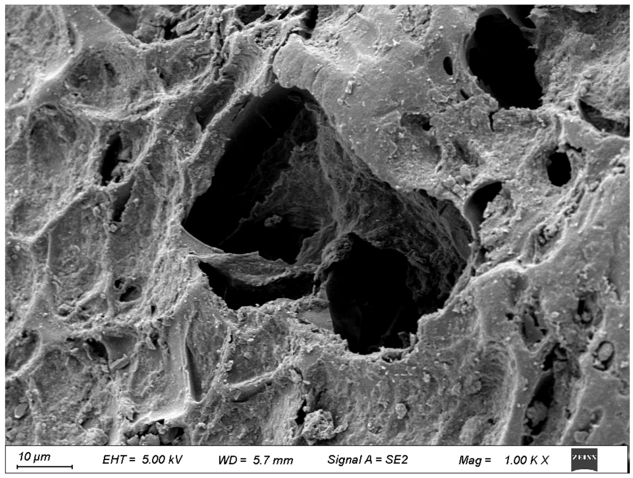
3.2. Pore Structure Analysis of Biochar (BET)

Nitrogen adsorption-desorption isotherms and pore size distributions for raw and modified biochar are plotted in Figure 3. Both materials displayed Type IV isotherms with H3 hysteresis loops, demonstrating that their pore frameworks are dominated by mesoporous structures, consistent with pore distribution curve observations.

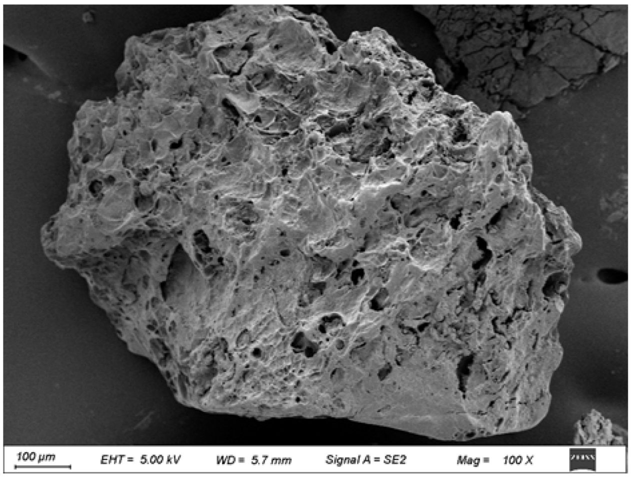
BET-derived structural parameters (Table 3) indicated that $KMnO_4$-modified biochar had a specific surface area of 114.011 $m^2 \cdot g^{-1}$, representing a 22.776% increase relative to unmodified straw biochar. This enhancement arises from dual mechanisms of oxidative etching and manganese oxide deposition. As a strong oxidant, $KMnO_4$ ablates biochar outer layers to generate abundant micropores and raise total pore volume; concurrently, amorphous manganese oxide precipitates attach to biochar surfaces to supply additional adsorption sites. The expanded porous framework grants modified biochar superior heavy metal retention capacity (Yin et al., 2023).



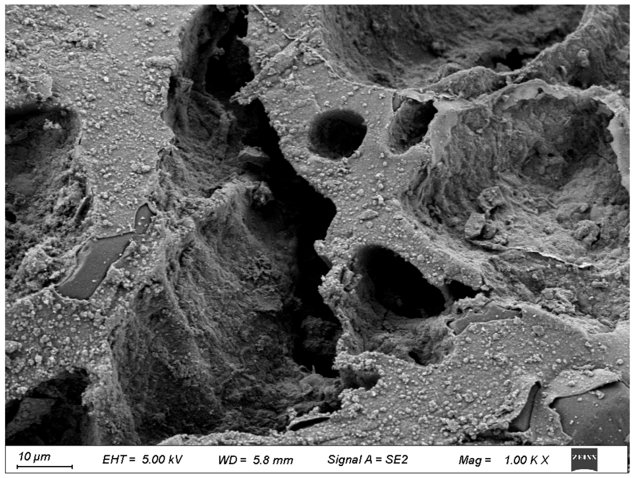
(a) biochar at 100X



(b) biochar at 1000x

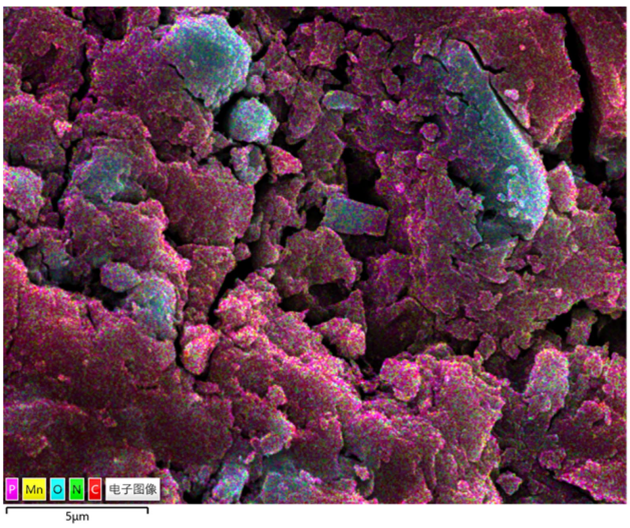


(c) Potassium permanganate modified biochar at 100X

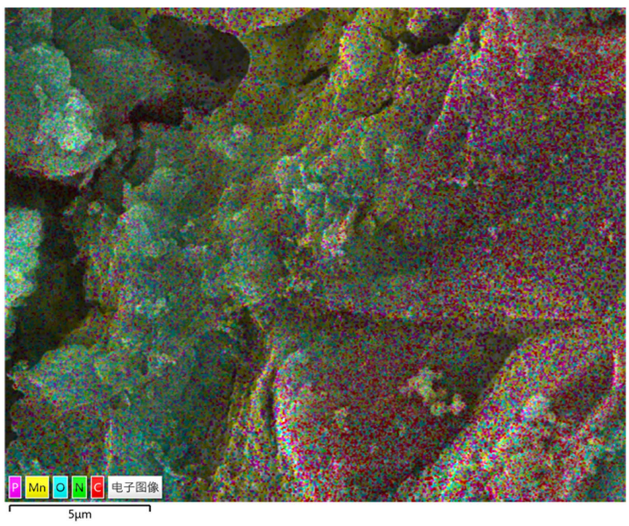


(d) Potassium permanganate modified biochar at 1000X

Figure 1. Scanning electron microscope of biochar (SEM).



Biochar



Potassium permanganate modified biochar

Figure 2. Elements contained on the surface of biochar before and after modification (Mapping).

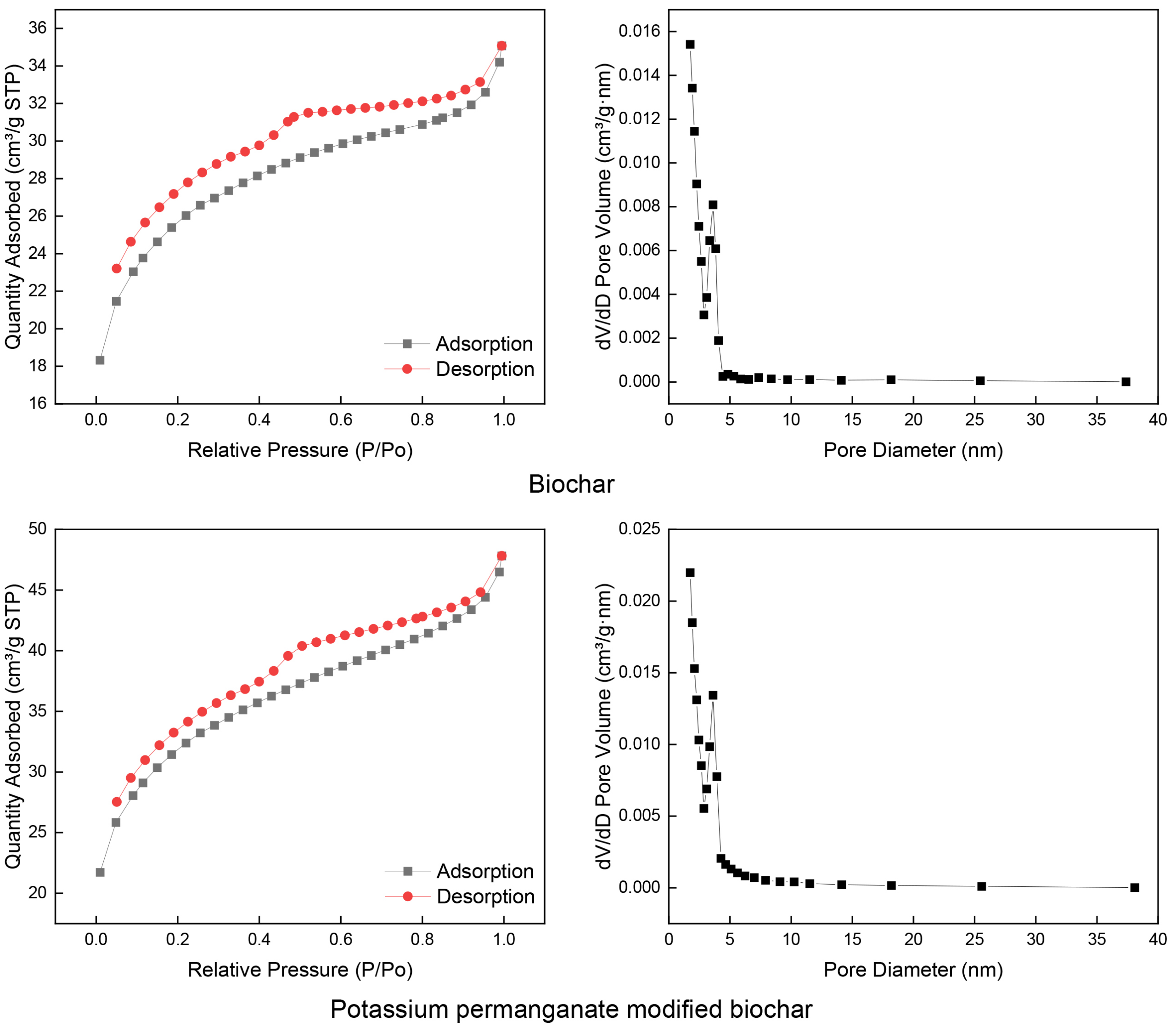


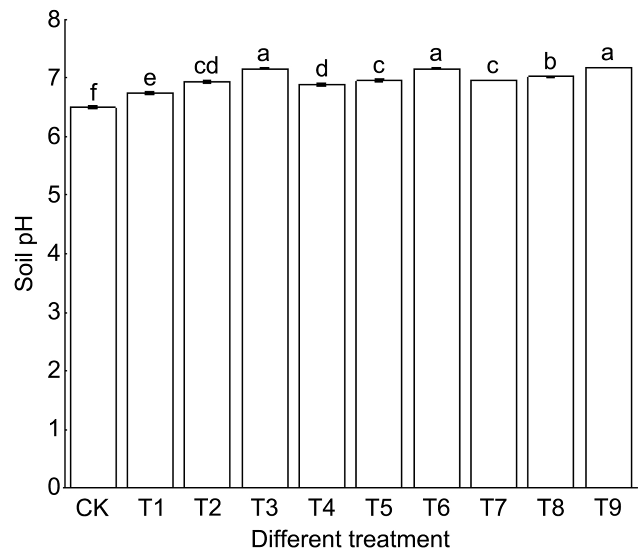
Figure 3. Biochar N_2 adsorption-desorption isotherm, pore size distribution (BET).

Table 3. Specific surface area, pore volume and average pore diameter of biochar.

Material Science	Specific surface area (m^2/g)	Pore volume (cm^3/g)	Average aperture (nm)
Biochar	92.861	0.054	3.148
Potassium permanganate modified biochar	114.011	0.074	3.408

3.3. Effect of Biochar Based Organic Fertilizer on pH of Cadmium Contaminated Soil

All fertilization treatments significantly elevated soil pH relative to the unamended CK blank (Figure 4). The three highest-dosage treatments (T3, T6, T9) produced the strongest neutralizing effects, raising soil pH by 0.66, 0.67, and 0.69 units versus CK, respectively. Even the lowest dosage of conventional organic fertilizer (T1), 1500 kg·ha^{-1} significantly increased soil pH by 0.250 units, confirming low-rate organic inputs can mitigate soil acidity. For all three fertilizer types, pH-amending capacity increased monotonically with rising application dosage, with the 4500 kg·ha^{-1} gradient generating maximum pH elevation across all amendment groups.



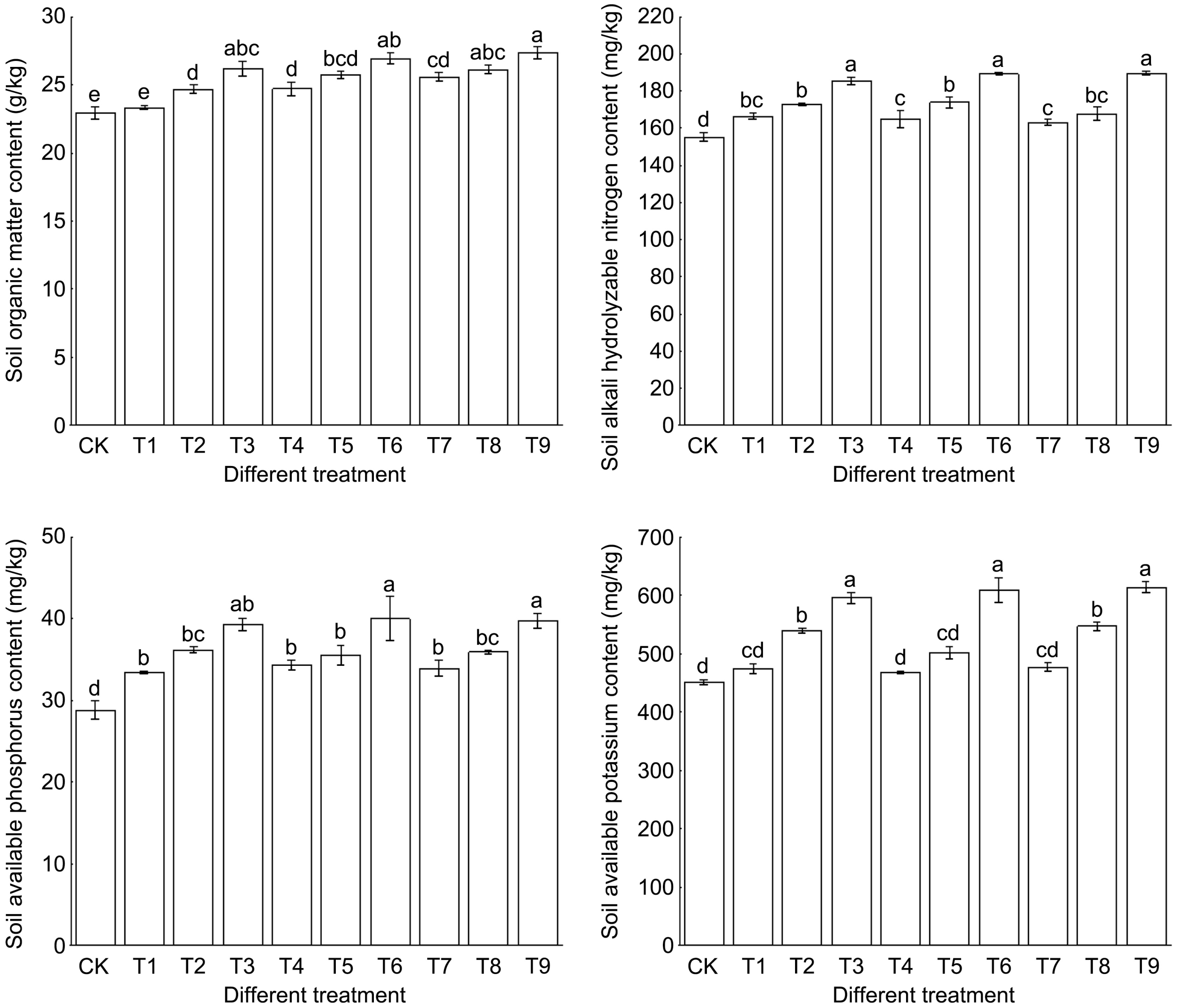
Note: blank control (CK), 1500 kg·ha^{-1} (T1), 3000 kg·ha^{-1} (T2), 4500 kg·ha^{-1} (T3), 1500 kg·ha^{-1} (T4), 3000 kg·ha^{-1} (T5), 4500 kg·ha^{-1} (T6), 1500 kg·ha^{-1} (T7), 3000 kg·ha^{-1} (T8), 4500 kg·ha^{-1} (T8) and 4500 kg·ha^{-1} (T5), respectively kg·ha^{-1} (T9); There was significant difference in the expression of different letters ($P < 0.05$).

Figure 4. Effect of different treatments on soil pH.

3.4. Effects of Biochar Based Organic Fertilizer on Organic Matter and Available Nutrients in Cadmium Contaminated Soil

All amendment treatments significantly elevated soil organic matter, alkaline-hydrolyzable nitrogen, available phosphorus, and available potassium compared with CK (Figure 5). Treatment T9 (4500 kg·ha^{-1} modified biochar fertilizer II) delivered the largest gains in organic matter (+43.661%), alkaline-hydrolyzable nitrogen (+22.195%), and available potassium (+36.243%). By contrast, T6 (4500 kg·ha^{-1} raw biochar fertilizer I) maximized soil available phosphorus with a 39.005% increment over CK. The minimal dosage of conventional organic fertilizer (T1, 1500 kg·ha^{-1}) generated the weakest nutrient enrichment, raising organic matter and available phosphorus by only 15.988% and 16.110%, respectively. These data demonstrate that even low-rate organic amendments replenish soil nutrient pools, while high-rate modified biochar compound fertilizer optimizes organic carbon and macronutrient availability. The linear rise in available nutrients may be partially attributed to the proportional elevation in basal nutrient inputs driven by increasing biochar-based fertilizer application rates.

Across all four fertility indices measured in this trial, the 4500 kg·ha^{-1} dosage of $KMnO_4$-modified biochar fertilizer II achieved the most comprehensive improvement in red earth nutrient status.

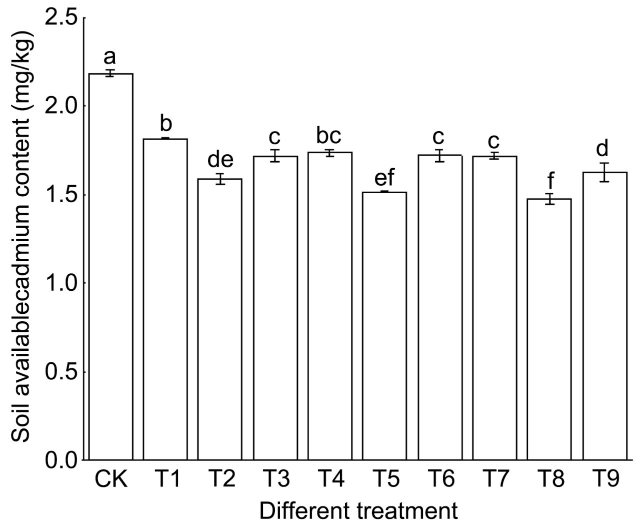


Note: blank control (CK), 1500 kg·ha^{-1} (T1), 3000 kg·ha^{-1} (T2), 4500 kg·ha^{-1} (T3), 1500 kg·ha^{-1} (T4), 3000 kg·ha^{-1} (T5), 4500 kg·ha^{-1} (T6), 1500 kg·ha^{-1} (T7), 3000 kg·ha^{-1} (T8), 4500 kg·ha^{-1} (T8) and 4500 kg·ha^{-1} (T5), respectively kg·ha^{-1} (T9); There was significant difference in the expression of different letters ($P < 0.05$).

Figure 5. Effects of different treatments on soil organic matter and available nutrient content.

3.5. Effect of Biochar Based Organic Fertilizer on Available Cadmium Content in Cadmium Contaminated Soil

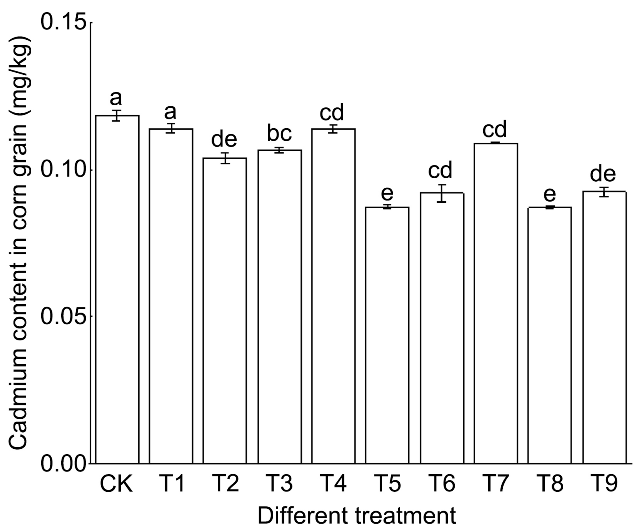
Every fertilization regime significantly lowered DTPA-extractable (labile) soil Cd relative to CK (Figure 6). Treatment T8 (3000 kg·ha^{-1} modified biochar fertilizer II) generated the strongest Cd immobilization effect, reducing labile soil Cd by 32.842% versus CK. The lowest dosage of conventional organic fertilizer (T1) produced the weakest passivation effect, with extractable Cd declining by only 16.914%. Although minimal organic fertilizer inputs already suppress soil Cd bioavailability, the 3000 kg·ha^{-1} gradient of $KMnO_4$-modified biochar compound fertilizer represented the optimal dosage for reducing labile Cd pools in mining red earth.



Note: blank control (CK), 1500 kg·ha^{-1} (T1), 3000 kg·ha^{-1} (T2), 4500 kg·ha^{-1} (T3), 1500 kg·ha^{-1} (T4), 3000 kg·ha^{-1} (T5), 4500 kg·ha^{-1} (T6), 1500 kg·ha^{-1} (T7), 3000 kg·ha^{-1} (T8), 4500 kg·ha^{-1} (T8) and 4500 kg·ha^{-1} (T5), respectively kg·ha^{-1} (T9); There was significant difference in the expression of different letters ($P < 0.05$).

Figure 6. Effect of different treatments on soil available cadmium content.

3.6. Effect of Biochar Based Organic Fertilizer on Cadmium Content in Maize Grain



Note: blank control (CK), 1500 kg·ha^{-1} (T1), 3000 kg·ha^{-1} (T2), 4500 kg·ha^{-1} (T3), 1500 kg·ha^{-1} (T4), 3000 kg·ha^{-1} (T5), 4500 kg·ha^{-1} (T6), 1500 kg·ha^{-1} (T7), 3000 kg·ha^{-1} (T8), 4500 kg·ha^{-1} (T8) and 4500 kg·ha^{-1} (T5), respectively kg·ha^{-1} (T9); There was significant difference in the expression of different letters ($P < 0.05$).

Figure 7. Effect of different treatments on cadmium content in maize grain.

All fertilizer applications reduced Cd accumulation in maize grains relative to the unamended control (Figure 7). Treatments T5 (3000 kg·ha^{-1} raw biochar fertilizer I) and T8 (3000 kg·ha^{-1} modified biochar fertilizer II) yielded identical maximal grain Cd suppression, lowering grain Cd concentrations by 26.271% compared with CK. The minimal conventional organic fertilizer treatment T1 only achieved a marginal 3.390% reduction in grain Cd content. All amendment treatments achieved statistically significant declines in grain Cd concentration. Among them, high-dose application regimes represented by T5, T6, T8 and T9 lowered maize grain Cd to less than the stringent food safety threshold of 0.1 mg·kg^{-1}, thereby producing Cd-safe edible grains for human intake.

For both raw and $KMnO_4$-modified biochar compound fertilizers, the 3000 kg·ha^{-1} application dosage delivered optimal inhibition of Cd translocation into maize reproductive tissues.

3.7. Effect of Biochar Based Organic Fertilizer on Maize Growth

Fertilization generally improved maize agronomic performance, though significant differences relative to CK were not observed for all measured indices across every treatment (Table 4). Treatment T9 (4500 kg·ha^{-1} modified biochar fertilizer II) achieved the maximum grain yield, with a 64.078% increment over the blank control, confirming the high dosage of modified biochar compound fertilizer optimizes maize productivity in Cd-polluted mining red earth.

Table 4. Effects of different treatments on maize growth.

	Yield (kg)	Plant height (m)	Crown width (m)	Leaf length (m)
CK	10.300 ± 0.100b	2.827 ± 0.020b	0.095 ± 0.002b	0.927 ± 0.015b
T1	12.400 ± 0.929ab	2.893 ± 0.043bc	0.097 ± 0.002b	0.943 ± 0.029ab
T2	14.000 ± 0.308ab	2.927 ± 0.010ab	0.096 ± 0.005b	0.983 ± 0.018ab
T3	14.533 ± 0.616ab	2.937 ± 0.022ab	0.097 ± 0.001b	0.997 ± 0.012ab
T4	12.367 ± 0.900ab	2.867 ± 0.017bc	0.098 ± 0.001b	0.983 ± 0.007ab
T5	14.000 ± 1.913ab	2.910 ± 0.000abc	0.098 ± 0.002b	1.000 ± 0.010a
T6	14.513 ± 1.967ab	2.943 ± 0.010ab	0.103 ± 0.003ab	1.007 ± 0.009a
T7	13.767 ± 1.900ab	2.893 ± 0.010bc	0.097 ± 0.002b	0.987 ± 0.003ab
T8	14.867 ± 0.694ab	2.913 ± 0.010abc	0.105 ± 0.005ab	1.007 ± 0.009a
T9	16.900 ± 1.570a	2.990 ± 0.017a	0.115 ± 0.003a	1.013 ± 0.012a

Fertilization consistently promoted maize vegetative growth where statistical significance was detected. T9 produced the largest improvements in plant height (+0.163 m), canopy width (+21.053%), and functional leaf length (+9.277%) relative to CK.

At the maximum 4500 kg·ha^{-1} application gradient, maize vegetative growth promotion followed the performance sequence T9 > T6 > T3, corresponding to modified biochar fertilizer II > raw biochar fertilizer I > conventional manure fertilizer.

However, it should be noted that because the N, P, and K inputs were not strictly balanced across treatments, part of the observed treatment effect on maize growth and productivity may reflect the increased macronutrient supply from the higher fertilizer application rates, rather than being solely attributable to the structural and chemical mechanisms of the $KMnO_4$-modified biochar.

4. Discussion

4.1. Effects of Biochar Based Organic Fertilizer on Physical and Chemical Properties of Cadmium Contaminated Soil and Crop Growth

Biochar-manure compound amendments improve soil physical structure, neutralize acidic red earth, and supply sustained macronutrient release to facilitate crop nutrient uptake (Chen et al., 2022; Zhang et al., 2020). Consistent with these universal mechanisms, all three tested fertilizers ameliorated Cd-polluted mining soil by elevating pH, replenishing labile nutrient pools, and stimulating maize vegetative and reproductive growth. The 4500 $kg \cdot ha^{-1}$ dosage of $KMnO_4$-modified biochar fertilizer II delivered the greatest fertility gains (**Figure 4**, **Figure 5**), attributable to the inherently alkaline nature and high organic carbon content of all manure-biochar blends (**Table 1**). High amendment inputs deliver abundant alkaline substances and organic residues to raise soil pH and accumulate available nutrients; additional biochar particles incorporated at high dosages further amplify these soil quality improvements. Our field observations align with previous regional research: biochar additions raise soil pH and plant-available nutrients in acid upland soils (Li et al., 2025b), and carbon-based organic fertilizers boost N, P, K availability in temperate croplands (Rashid et al., 2021). Biochar's porous matrix retains ammonium and nitrate ions to mitigate nitrogen leaching and accelerate organic nitrogen mineralization, a core fertility regulation mechanism validated by Lehmann et al. (2003).

4.2. Effects of Biochar Based Organic Fertilizer on Heavy Metals in Cadmium Contaminated Soil

Soil pH and organic carbon pools are the primary regulators of Cd bioavailability in acid mining soils (Li et al., 2024). Elevated pH increases negative surface charge on soil colloids, strengthening electrostatic attraction for cationic Cd^{2+}; soil organic matter concurrently binds soluble Cd into stable organo-metallic complexes that cannot be readily absorbed by cereal crops (Xue et al., 2024). Consistent with these dual passivation pathways, all three manure-biochar blends lowered labile soil Cd and grain Cd accumulation in this field trial, with the 3000 $kg \cdot ha^{-1}$ dosage of both biochar fertilizers delivering optimal Cd suppression (**Figure 7**). More critically, when deployed in actual field production, it successfully interrupts cadmium transfer along the food chain and safeguards the food safety of harvested agricultural commodities. The superior passivation performance of modified biochar fertilizer II originates from its enlarged BET specific surface area (**Table 3**), generated via $KMnO_4$ oxidative etching and Mn oxide loading, which multiplies physical adsorption, ion exchange, and electrostatic binding sites for Cd ions. Existing literature confirms biochar physicochemical traits govern Cd immobilization efficiency in polluted croplands: biochar sequesters Cd via multiple interfacial mechanisms and shifts metal fractions toward residual, non-bioavailable pools (Rahim et al., 2022; Luo et al., 2022). Combined biochar-mineral amendments also stabilize dissolved Cd by elevating soil solution pH (Su et al., 2024), while straw-derived biochar serves as a recyclable waste resource for Cd remediation (Sun et al., 2023). Notably, species-specific discrepancies exist: biochar may boost Cd uptake in leafy vegetables such as pakchoi despite improving plant biomass (Zhang et al., 2026), highlighting the necessity of field trials targeting staple grain crops like maize in local mining soils.

4.3. Divergence in Optimal Application Rates for Cd Remediation versus Crop Productivity

A clear divergence emerged between the optimal application rates for environmental remediation and agricultural productivity. While the reduction of bioavailable Cd peaked at 3000 $kg \cdot ha^{-1}$ (**Figure 7**), the maximum maize yield and optimal vegetative growth were achieved at 4500 $kg \cdot ha^{-1}$ (**Figure 4**, **Figure 5**). This contrast highlights the differing mechanisms governing heavy metal immobilization versus crop nutritional demands.

For Cd passivation, the 3000 $kg \cdot ha^{-1}$ dosage likely reaches a chemical immobilization threshold. At this rate, the modified biochar provides sufficient binding sites—via its porous architecture and surface functional groups—to stabilize the labile Cd present in the soil (Rahim et al., 2022; Luo et al., 2022). Further additions do not significantly enhance remediation efficiency, as the passivation process becomes limited by the remaining labile Cd concentration rather than a lack of available binding sites (Li et al., 2017).

Conversely, crop productivity is driven by a continuous biological demand for macronutrients and organic matter (Chen et al., 2022). The 4500 $kg \cdot ha^{-1}$ dosage maximizes basal nutrient inputs, fulfilling the higher nutritional threshold required to sustain vigorous vegetative and reproductive growth (Rashid et al., 2021; Zhang et al., 2020).

Therefore, application strategies should be tailored to specific regional objectives. For scenarios strictly prioritizing the cost-effective remediation of Cd-polluted mining soils, 3000 $kg \cdot ha^{-1}$ serves as the optimal dosage. However, if the primary objective is to maximize agricultural crop yield alongside environmental risk mitigation, a higher application rate of 4500 $kg \cdot ha^{-1}$ is recommended.

5. Conclusion

1) $KMnO_4$ oxidative reconstruction generates abundant surface fractures and hierarchical meso-micropore networks on maize straw biochar. The modified ma-

terial achieves a specific surface area of 114.011 $m^2 \cdot g^{-1}$, a 22.776 increment relative to raw straw biochar.

2) All three manure-biochar compound fertilizers improve the physicochemical fertility of Cd-contaminated plateau red earth, with $KMnO_4$-modified biochar fertilizer II showing the strongest comprehensive benefits. At 4500 $kg \cdot ha^{-1}$ (T9), soil pH rose by 0.69 units, organic matter increased by 43.661%, alkaline-hydrolyzable nitrogen increased by 22.195%, and available potassium increased by 36.243%.

3) All three amendments (conventional organic fertilizer, biochar-based organic fertilizer I and biochar-based organic fertilizer II) substantially reduce labile soil Cd and inhibit Cd accumulation in maize grains. Treatments T5 and T8 exhibit outstanding efficacy in lowering grain Cd concentration, with grain Cd content decreased by 26.271% relative to CK. The 3000 $kg \cdot ha^{-1}$ dosage of $KMnO_4$-modified biochar fertilizer II (T8) achieves the most prominent immobilization of soil labile Cd: DTPA-extractable soil Cd declines by 32.842%, outperforming conventional organic fertilizer and unmodified biochar-based organic fertilizer I.

4) The 4500 $kg \cdot ha^{-1}$ high dosage of modified biochar fertilizer II maximizes maize grain yield and vegetative morphological traits, raising grain output by 64.078%, plant height by 0.163 m, canopy width by 21.052%, and functional leaf length by 9.277%. Across all dosage gradients, modified biochar compound fertilizer consistently outperforms raw biochar fertilizer and conventional manure for maize growth promotion.

In summary, $KMnO_4$-modified biochar-manure compound fertilizer integrates multiple advantages of red earth acid neutralization, nutrient enrichment, Cd immobilization, and maize yield promotion at high field application dosages, serving a viable remediation material for mining-contaminated uplands across Southwest China. Practical constraints include elevated biochar manufacturing and transportation costs, limiting large-scale deployment to regions with abundant straw biomass resources nearby. Further field multi-year trials and cost optimization research are required to stabilize field performance and expand on-farm applicability of this remediation technology.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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