Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Mitigation of Cd accumulation in rice by the combined of Mg-modified biochar/attapulgite materials and foliar inhibitors

Jilei Fang
School of Energy and Environment, Southeast University
Wenxuan Luo
School of Energy and Environment, Southeast University
Jizhuang Wu
Yantai Academy of Agricultural Sciences
Kunpeng Yang
School of Energy and Environment, Southeast University
Yaping Zhang
amflora@seu.edu.cn

School of Energy and Environment, Southeast University

Research Article

Keywords: Heavy metal pollution, Biochar modification, Clay minerals, Foliar inhibitor, Field experiment

Posted Date: July 6th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9732921/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Cadmium (Cd) is a highly toxic heavy metal that poses serious threats to both human health and plant growth. It exhibits several environmental risks, including high enrichment potential, mobility, chemical stability, long persistence in soil, and resistance to microbial degradation. In this study, a novel Mg-modified biochar/palygorskite composite material was developed and applied in field experiments to evaluate its effects on soil pH, organic matter content, as well as the speciation and concentration of Cd. Furthermore, the effectiveness of integrating foliar control techniques in mitigating Cd accumulation across various rice tissues was investigated. The experimental results demonstrated $MgCl_2$/BA and MgO/BA increased soil pH by 0.46 and 0.53 units, respectively, resulting in a 41.02% and 38.83% increase in soil organic matter content. At the same time, the available Cd content in the soil significantly decreased, as the acid-soluble and reducible fractions of Cd were transformed into oxidizable and residual forms. Besides, Cd content in rice grains treated with $MgCl_2$/BA and MgO/BA decreased by 66.22% and 72.90% respectively. After the foliar application of the remediation agent, the Cd content in rice grains further decreased by 20.54% and 13.22% respectively. Moreover, the application of the remediation agent contributed to an increase in rice yield.

1.Introduction

The problem of heavy metal pollution in soil has drawn extensive attention from society[1]. Cadmium (Cd) is one of the heavy metal elements with high toxicity to both humans and plants [2, 3]. Cd exhibits several characteristics that contribute to its environmental persistence and mobility, including a strong tendency to accumulate, high stability, long retention time in soils, limited biodegradability, and relatively high mobilitys [4]. Elevated levels of Cd in soil not only degrade soil physicochemical properties but also adversely affect plant growth and development, leading to reduced growth rates, nutritional imbalances, inhibited photosynthesis, and ultimately decreased crop yields [5, 6]. Furthermore, Cd can be readily taken up by crops and subsequently transferred through the food chain, posing serious threats to human health [7, 8].

To address the issue of soil Cd pollution, various remediation methods have been developed and widely applied. Among these approaches, stabilization technology demonstrates considerable application potential, attributed to its operational simplicity, cost-effectiveness, environmental compatibility, and the capacity to concurrently immobilize multiple heavy metal contaminants [9, 10]. Biochar, characterized by its low cost, large specific surface area, and abundant functional groups, has been extensively utilized in soil remediation [11]. The immobilization of heavy metals by biochar primarily occurs through two mechanisms: (i) direct adsorption via electrostatic attraction, complexation, ion exchange, precipitation, and physical adsorption; and (ii) enhancement of soil particle adsorption capacity through modifications of physicochemical properties such as soil pH, cation exchange capacity (CEC), and mineral and organic matter content, thereby stabilizing heavy metals [12–14]. To improve the pollutant removal efficiency of biochar, chemical and physical modification techniques are commonly employed to alter its original structure and surface characteristics. Among various metal oxides, MgO is regarded as an effective and

suitable modifier due to its abundant natural availability and low toxicity [15]. MgO has been extensively studied for soil improvement owing to its economic viability and environmental safety. Compared with other metal oxides, the release of Mg^{2+} from MgO results in relatively lower environmental risks [16, 17]. Researches indicates that $MgCl_2$ modification reduces the specific surface area and aromaticity of biochar while increasing its pH and polarity, along with a higher number of oxygen-containing functional groups—changes that collectively enhance the stabilization of Cd [18, 19].

In recent years, natural mineral materials have emerged as a focal point in environmental research. These materials can effectively reduce the bioavailability of heavy metals in contaminated soils through various mechanisms, including adsorption, coprecipitation, complexation, and ion exchange, thereby facilitating soil remediation [20]. Due to their abundant availability, low economic cost, and minimal ecological impact, natural minerals such as bentonite, attapulgite, sepiolite, and zeolite are increasingly utilized in the passivation-based remediation of farmland soils contaminated with heavy metals [21, 22]. Attapulgite, a hydrated magnesium-aluminum silicate mineral, possesses a unique two-dimensional layered and fibrous structure, along with a distinct layer-chain crystalline arrangement [23]. Its strong adsorption capacity, combined with its wide natural distribution and economic viability, has led to its growing application in environmental restoration practices over the past decade [24, 25]. Numerous studies have demonstrated that attapulgite significantly reduces the bioavailable fraction of heavy metals in soil, contributing to improved soil quality [26, 27]. Therefore, combining biochar with attapulgite into composite materials is expected to enhance the efficiency of Cd immobilization in contaminated soils [28]. However, under real-world remediation conditions, the performance of such composites often falls short of theoretical expectations. Consequently, integrating these materials with complementary technologies is essential to further minimize Cd accumulation in rice grains. Foliar control technology offers dual benefits: it not only suppresses plant uptake and translocation of Cd but also promotes overall plant growth and enhances crop yield [29, 30]. This approach directly targets the plant system, primarily functioning by stimulating the absorption of beneficial trace and micronutrients, which in turn inhibits the uptake and transport of toxic heavy metals [31, 32]. Evidence from previous studies supports the effectiveness of foliar control agents in reducing Cd concentrations in rice grains [33–35]. Nevertheless, limited research has explored the synergistic use of soil passivators and foliar control agents. Thus, further investigation is warranted to evaluate the combined efficacy of these two approaches under actual field conditions.

This study synthesized various Mg-modified biomass/attapulgite composite materials and employed field experiments to systematically analyze alterations in soil physicochemical properties, the speciation transformation of Cd in contaminated soils, and the impact of integrated foliar control strategies on cadmium accumulation across different rice tissues. The practical effectiveness of these combined approaches under real-field conditions was also evaluated, aiming to enhance the understanding of remediation mechanisms in paddy fields and provide scientific and technical support for the development of efficient and environmentally friendly materials for heavy metal pollution remediation.

2. Materials and Methods

2.1 Material Preparation and Modification

The biomass raw materials were thoroughly rinsed with deionized water and then dried in an oven at 80°C until reaching a constant weight. Subsequently, they were ground using a pulverizer and passed through a 60 - mesh sieve before being sealed for storage. Attapulgite and the biomass raw materials were blended at a mass ratio of 1:1. Then, 2 mol of $MgCl_2 \cdot 2H_2O$ or MgO was added to the mixture, along with 1 L of deionized water. The resulting mixture was subjected to ultrasonic treatment for 30 min and magnetic stirring for 24 h. After drying the mixture at 80°C, an appropriate quantity was placed into a quartz tube. Under a nitrogen atmosphere, pyrolysis was carried out in a tube furnace at a temperature of 600°C with a heating rate of 10°C/min for 1 h. Upon completion of the pyrolysis process, the sample was allowed to cool naturally to room temperature. The synthesized composite material was then retrieved and washed multiple times with deionized water until the pH value reached 7.0. Finally, the product was dried under the condition of 105°C. The attapulgite - biochar composite material without magnesium modification was prepared using the same method. The original biochar, biochar/attapulgite composite material, $MgCl_2$-modified biochar/attapulgite composite material, and MgO-modified biochar/attapulgite composite material were designated as B, BA, $MgCl_2$/BA, and MgO/BA, respectively.

2.2 Field Experiment Design

The experimental site is located in a farmland in Xuzhou City, Jiangsu Province in China (E: 117°59'~118°39', N: 34°06'~34°26'), which belongs to a temperate monsoon climate. The field experiment area is 20 mu, and a randomized block design is adopted. A total of 10 treatments are set up, with three replicates for each treatment. These include five treatments without foliar barrier agents: CK, B, BA, $MgCl_2$/BA and MgO/BA, as well as the corresponding treatments with foliar inhibitor added. 15 days before rice planting, the prepared passivation materials were evenly spread on the soil and mixed with the soil through ploughing, with a ploughing depth of 20 cm. The soil and the remediation materials were kept in a flooded state for 7 days. Field management was carried out according to normal agricultural practices. The soil Cd concentrations were 0.30 mg/kg, 0.36 mg/kg, 0.40 mg/kg, 0.52 mg/kg, and 0.55 mg/kg. During the field experiment, the pH of atmospheric precipitation was 8.51, with a Cd content less than 0.0002 mg/L; the Cd content of atmospheric deposition was 1.49 mg/kg; the pH of irrigation water was 6.97, with a Cd content less than 0.0002 mg/L; the applied fertilizers were urea and compound fertilizer, with Cd content in urea being 0.0051 mg/kg and P content being 0.0082%, and Cd content in compound fertilizer being 0.076 mg/kg and P content being 9.62%. The foliar barrier agent sprayed in the experiment was a silicon-based foliar inhibitor, and its basic characters are as follows: Si ≥ 85 g/L, Na ≤ 10.0 g/L, pH: 6, water-insoluble matter ≤ 10.0 g/L.

2.3 Collection and analysis of samples

Soil samples (0–20 cm) and whole rice plants were collected at the rice maturity stage. The soil samples were air-dried, ground, and sieved through 10-mesh and 100-mesh sieves for later use. The rice samples were washed, blanched at 105°C for 30 minutes, and dried at 75°C to a constant weight. The collected rice samples were divided into five parts: roots, stems, leaves, grains, and husks. Each part was ground

with a stainless steel grinding machine and sieved through a 100-mesh sieve. Soil pH was measured by electrode method (soil-to-water ratio of 1:2.5), and soil organic matter content was determined by the potassium dichromate dilution heat method. The available forms of heavy metals in soil were extracted with 0.1 mol/L DTPA solution (soil-to-liquid ratio of 1:10). The Cd content in each part of the plants was determined after digestion with HNO_3-H_2O_2, and the total Cd content in soil was determined after digestion with HNO_3-HCl-$HClO_4$. The chemical forms of Cd in soil were extracted by the BCR method, and quality control was performed using standard substances. The determination was carried out using ICE-OES (OPTIMA 8000DV PerkinElmer). The surface morphology of diverse materials was detected through scanning electron microscopy (SEM, Zeiss Sigma 300, Germany) along with energy dispersive X-ray spectroscopy (EDS)

3.Results and discussion

3.1 Morphological characteristics of materials

Figure 1 presents the SEM-EDS images of raw biochar (B), biochar/attapulgite composite (BA), magnesium chloride-modified biochar/attapulgite composite ($MgCl_2$/BA), and magnesium oxide-modified biochar/attapulgite composite (MgO/BA). SEM analysis reveals that the raw biochar exhibits a well-defined porous structure, which offers advantageous sites for the effective loading of attapulgite. Following the incorporation of attapulgite, needle-like crystalline structures are clearly visible on the surfaces of both composite materials, providing visual evidence of successful attapulgite immobilization [36]. Furthermore, EDS spectral analysis demonstrates that the surface Mg content in both MgO/BA and $MgCl_2$/BA composites is markedly higher compared to that in B and BA, confirming the effective modification of the composites with magnesium compounds.

3.2. Basic properties of soil

Figure 2a illustrates the changes in soil pH during the rice harvest period. Compared with the control (CK), all four applied materials effectively increased soil pH. Specifically, the pH values in treatments B and BA increased by 0.32 and 0.39 units, respectively, relative to CK. The $MgCl_2$/BA treatment resulted in a pH increase of 0.46 units. Notably, MgO modification exhibited the most significant effect on pH elevation, with an increase of 0.53 units. This enhanced alkalinity may be attributed to the reaction of MgO with water, leading to the formation of alkaline compounds that substantially raise soil pH.

Figure 2b presents the effects of different treatments on soil organic matter content. Compared with the control (CK) from the same plot, all composite material treatments led to an increase in organic matter content, following the order: MgO/BA>$MgCl_2$/BA > B>BA. Specifically, the MgO-modified material increased soil organic matter by 38.83%, while the $MgCl_2$-modified material resulted in a 41.02% increase compared to the original biochar. This enhancement can be attributed to the application of biochar, which significantly elevates carbon and nitrogen concentrations in soil organic components, thereby promoting the accumulation of soil organic matter[37]. On one hand, carbon materials contribute to

organic matter during their decomposition process and facilitate humus formation, thus improving soil fertility. On the other hand, carbon materials themselves promote aggregate formation by adsorbing organic molecules and catalyzing their polymerization into stable soil organic matter through surface catalytic activity [38].

3.3. Soil Cd chemical fractions and available content

As illustrated in Fig. 3, the application of biochar and composite materials resulted in a reduction in the acid-soluble and reducible fractions of soil Cd, while the oxidizable and residual fractions showed slight increases. Following passivation with raw biochar, the acid-soluble and reducible forms decreased from 54.50% and 25.53% to 52.82% and 23.62%, respectively, whereas the oxidizable and residual forms increased from 11.79% and 8.17% to 14.02% and 9.53%. After BA treatment, the acid-soluble and reducible forms dropped to 51.05% and 15.94%, respectively, with the residual form rising to 13.94%. Compared with CK, $MgCl_2$-modified composite material reduced the acid-soluble and reducible forms by 4.72% and 8.33%, respectively, while increasing the residual form by 7.66%. The MgO-modified composite further enhanced this effect, reducing the acid-soluble and reducible forms by 9.09% and 8.94%, respectively, while increasing the oxidizable and residual forms by 8.75% and 9.28%. These results indicate that both Mg-modified composites effectively transformed unstable Cd fractions into more stable forms. The immobilization of heavy metals by biochar/attapulgite composites is governed by multiple mechanisms. Previous studies have shown that carbon-based materials influence Cd bioavailability through both electrostatic and non-electrostatic interactions [39]. Electrostatic effects involve alterations in soil surface charge characteristics, which are crucial for interactions between heavy metals and variable-charge soils. Non-electrostatic mechanisms include three primary pathways: (1) oxygen-containing functional groups (e.g., carboxyl and hydroxyl groups) on the carbon surface can form surface complexes with heavy metals; (2) aromatic structures rich in π-electrons may interact with metals via π–π electron interactions; and (3) anionic functional groups such as hydroxyl, carbonate, and phosphate can induce precipitation reactions with heavy metals in soil[40, 41]. Due to changes in soil physicochemical properties, along with surface precipitation, ion exchange, adsorption, and complexation involving Cd^{2+} on Mg-modified composites, these materials facilitate the transformation of acid-soluble and reducible Cd into more stable oxidizable and residual forms.

Furthermore, the application of the four passivators led to a reduction in the available Cd content to varying degrees. As illustrated in Fig. 4, compared with CK, the available Cd content decreased by 10.31%, 16.62%, 20.78%, and 28.97% under treatments B, BA, $MgCl_2$/BA, and MgO/BA, respectively. Notably, the $MgCl_2$- and MgO-modified composite materials resulted in reductions of 27.38% and 28.1%, respectively. These findings indicate that all four passivators can effectively reduce the availability of Cd in soil, with the two Mg-modified composites showing the most pronounced effects. This enhanced performance may be attributed to two main factors: first, Mg-modified composites can elevate both soil pH and organic matter content; second, Mg^{2+} ions can mitigate the impact of exchangeable Al^{3+} and H^+ on soil acidification, thereby reducing the bioavailability of Cd [42]. Consequently, the lowest available Cd

content and the most effective passivation were observed in soils treated with Mg-modified composite materials.

3.4. Cadmium content in various parts of rice

To investigate the effects of foliar control agents on crops, Cd concentrations in different plant tissues were compared before and after foliar application. As illustrated in Fig. 5, following treatment with raw biochar, reductions in Cd content were observed in rice roots, stems, leaves, husks, and grains across all treatments. Compared to CK, $MgCl_2$/BA reduced Cd levels by 50.44%, 57.43%, 67.42%, 75.25%, and 66.22% in roots, stems, leaves, husks, and grains, respectively, while MgO/BA achieved reductions of 53.97%, 72.58%, 73.07%, 82.80%, and 72.90%. In treatments without foliar agent application, BA, $MgCl_2$/BA, and MgO/BA all effectively reduced grain Cd content below 0.2 mg/kg, meeting the Chinese national standard for rice. Notably, MgO/BA exhibited the strongest effect, reducing grain Cd to 0.13 mg/kg. Therefore, compared with the original biochar and composite materials, Mg-modified composite materials not only improve soil physical and chemical properties and increase soil organic matter content, but also promote the conversion of available Cd into less bioavailable forms. Additionally, the release of Mg^{2+} may antagonize Cd^{2+} in the soil, thereby effectively reducing Cd accumulation in rice [43]. The application of foliar inhibitor agents further suppressed Cd accumulation in leaves, husks, and grains. However, Cd concentrations in roots and stems increased compared to those in non-foliar treatments, suggesting that the foliar agents successfully restricted Cd translocation from roots and stems to grains and husks. After foliar application, grain Cd levels under $MgCl_2$/BA and MgO/BA treatments decreased further to 0.13 and 0.11 mg/kg, representing reductions of 20.54% and 13.22%, respectively, compared to the same treatments without foliar application. These results can be attributed to the foliar application of silicon, which promotes the formation of a Si-Cd complex within the cell wall through interactions between hemicellulose-bound silicon and cadmium ions, thereby reducing the cytotoxic effects of cadmium[35, 44]. Heavy metal compartmentalization represents a crucial detoxification strategy that effectively reduces the concentration of free heavy metal ions in the cytoplasm, minimizing their toxic impact on cellular metabolism[33, 45]. Additionally, silicon application enhances the uptake of essential mineral nutrients (e.g., B, Cu, Fe, Mn, and Zn), some of which may compete with cadmium for the same transport pathways, thereby antagonizing Cd translocation within the plant[46, 47]. These findings demonstrate that the combined use of $MgCl_2$ or MgO-modified attapulgite/biochar composites with foliar control technology significantly reduces Cd accumulation in rice grains[48].

3.5. Analysis of crop yield and economic feasibility

The application of remediation materials also influenced crop yield in farmland soils. As shown in Fig. 6, the rice yield remained largely unchanged after the application of original biochar (BC) and the original composite material, at 599 kg/acre and 606 kg/acre, respectively. However, both treatments showed increased yields following the application of the foliar barrier agent. The $MgCl_2$-modified and MgO-modified composite materials further enhanced crop productivity. Specifically, rice yields reached 631

kg/acre and 628 kg/acre in plots treated with $MgCl_2$-modified and MgO-modified materials, respectively. Notably, the foliar inhibitor had no significant effect on the yield of the MgO-modified treatment, suggesting that the mineral elements present in the magnesium-based composite materials may have played a key role in promoting grain production[49].

The unit prices of the materials used in this study were as follows: rice straw biochar, 4,000 yuan per ton; attapulgite, 432 yuan per ton; $MgCl_2$-modified material, 1,980 yuan per ton; and MgO-modified material, 5,950 yuan per ton. The total cost for electricity, labor, and transportation during field experiment preparation amounted to 2,900 yuan. The overall costs of the four passivation materials, including labor, electricity, and transportation, are summarized in Table 1. Compared with the original biochar and original composite material, the $MgCl_2$-modified material reduced the cost by 903.84 yuan per ton and 428.11 yuan per ton, respectively. Similarly, the MgO-modified material showed a cost reduction of 648.19 yuan per ton compared to the original biochar and 172.46 yuan per ton compared to the original composite material.

Table 1
The cost of immobilization agent materials

immobilization agent materials	**Biochar**	**Biochar/ attapulgite**	**$MgCl_2$ Biochar/attapulgite**	**Mg Biochar/attapulgite**
Price (yuan per mu)	3925	3449.27	3021.16	3276.81

4. Conclusions

Field experiment results indicated that both magnesium-modified composite materials exhibited excellent performance in treating contaminated soil. Treatments with $MgCl_2$/BA and MgO/BA were able to elevate the soil pH by 0.46 and 0.53 units respectively, representing increases of 41.02% and 38.83% in soil organic matter content. Simultaneously, due to the transformation of acid-soluble and reducible fractions of soil Cd into oxidizable and residual fractions, the content of available Cd in soil treated with $MgCl_2$/BA and MgO/BA decreased significantly. The Cd content in rice grains treated with $MgCl_2$/BA and MgO/BA decreased by 66.22% and 72.90% respectively. After the foliar application of the remediation agent, the Cd content in rice grains further decreased by 20.54% and 13.22% respectively. Moreover, the application of the remediation agent contributed to an increase in rice yield. In terms of cost, the price of the $MgCl_2$-modified material was 903.84 yuan/ton and 428.11 yuan/ton lower than that of the original biochar and the original composite material respectively. The price of the MgO-modified material was 648.19 yuan/ton and 172.46 yuan/ton lower than that of the original biochar and the original composite material respectively.

Declarations

Declaration of Competing Interest

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

Funding

This work was financially supported by the National Key Research and Development Program of China (Grant No. 2023YFC3709600).

Author Contribution

Jilei Fang: Writing – original draft, Visualization, Data curation, Formal analysis, Conceptualization. Wenxuan Luo: Writing – original draft, Methodology, Investigation. Jizhuang Wu: Resources, Supervision. Kunpeng Yang: Writing – review & editing, Formal analysis, Validation, Data curation. Yaping Zhang: Supervision, Funding acquisition, Conceptualization.

References

1. Wang, H.M., Zhang H.H., Zhang X.F., Li Q., Cheng C.K., Shen H., and Zhang Z.Z., *Bioelectrochemical remediation of Cr(VI)/Cd(II)-contaminated soil in bipolar membrane microbial fuel cells*. Environmental Research, 186(2020), pp.
2. Xu, J.H., Hu C.Y., Wang M.L., Zhao Z.S., Zhao X.X., Cao L., Lu Y.F., and Cai X.Y., *Changeable effects of coexisting heavy metals on transfer of cadmium from soils to wheat grains*. Journal of Hazardous Materials, 423(2022), pp.
3. Du, Y.B., Tian Z.J., Zhao Y.F., Wang X.R., Ma Z.Z., and Yu C.H., *Exploring the accumulation capacity of dominant plants based on soil heavy metals forms and assessing heavy metals contamination characteristics near gold tailings ponds*. Journal of Environmental Management, 351(2024), pp.
4. Li, J., Zhang P.Y., Ye J.P., Zhang G.M., and Cai Y.J., *Simultaneous in-situ remediation and fertilization of Cd-contaminated weak-alkaline farmland for wheat production*. Journal of Environmental Management, 250(2019), pp.
5. Amen, R., Yaseen M., Mukhtar A., Klemes J.J., Saqib S., Ullah S., Al-Sehemi A.G., Rafiq S., Babar M., Fatt C.L., Ibrahim M., Asif S., Qureshi K.S., Akbar M.M., and Bokhari A., *Lead and cadmium removal from wastewater using eco-friendly biochar adsorbent derived from rice husk, wheat straw, and corncob.* Cleaner Engineering and Technology, 1(2020), pp.
6. Long, H.Y., Feng G.F., and Fang J., *In-situ remediation of cadmium contamination in paddy fields: from rhizosphere soil to rice kernel*. Environmental Geochemistry and Health, 46(2024), pp.
7. Zhong, M.T., Li W.D., Jiang M.H., Wang J.A., Shi X.Y., Song J.H., Zhang W.X., Wang H.J., and Cui J., *Improving the ability of straw biochar to remediate Cd contaminated soil: KOH enhanced the*

modification of K3PO4 and urea on biochar. Ecotoxicology and Environmental Safety, 262(2023), pp.

8. Zou, M.M., Zhou S.L., Zhou Y.J., Jia Z.Y., Guo T.W., and Wang J.X., *Cadmium pollution of soil-rice ecosystems in rice cultivation dominated regions in China: A review*. Environmental Pollution, 280(2021), pp.
9. Tang, B., Xu H.P., Song F.M., Ge H.G., Chen L., Yue S.Y., and Yang W.S., *Effect of biochar on immobilization remediation of Cd•contaminated soil and environmental quality*. Environmental Research, 204(2022), pp.
10. Jiang, Q., He Y.M., Wu Y.L., Dian B., Zhang J.L., Li T.G., and Jiang M., *Solidification/stabilization of soil heavy metals by alkaline industrial wastes: A critical review*. Environmental Pollution, 312(2022), pp.
11. He, Y.Y., Mi B.B., Luo C., Tao H.L., Zhang X., Yu J.W., Mo X.Y., Hu J., Chen L., Tu N.M., and Wu F.F., *A novel strategy employing lignin biochar to simultaneously promote remediation and safe crop production in Cd-contaminated soil*. Chemical Engineering Journal, 499(2024), pp.
12. Liu, Y.L., Luo H.Y., Tie B.Q., Li D.Y., Liu S.T., Lei M., and Du H.H., *The long-term effectiveness of ferromanganese biochar in soil Cd stabilization and reduction of Cd bioaccumulation in rice*. Biochar, 3(2021), pp. 499–509
13. Wang, Y.H., Yan Y.B., He C., Feng Y., Darma A., and Yang J.J., *The immobilization of cadmium by rape straw derived biochar in alkaline conditions: Sorption isotherm, molecular binding mechanism, and in-situ remediation of Cd-contaminated soil*. Environmental Pollution, 351(2024), pp.
14. Wu, Y., Yan Y.H., Wang Z.W., Tan Z.X., and Zhou T., *Biochar application for the remediation of soil contaminated with potentially toxic elements: Current situation and challenges*. Journal of Environmental Management, 351(2024), pp.
15. Yang, K.P., Guo B.Y., Shen K., Luo W.X., Zhang B., Hua Y.X., and Zhang Y.P., *Unraveling immobilization mechanisms of Cd in soil by MgO-modified palygorskite/biochar composite: DFT calculation and combined-artificial aging*. Journal of Environmental Management, 370(2024), pp.
16. Li, A.Y., Xie H.Q., Qiu Y., Liu L.H., Lu T., Wang W.H., and Qiu G.H., *Resource utilization of rice husk biomass: Preparation of MgO flake-modified biochar for simultaneous removal of heavy metals from aqueous solution and polluted soil*. Environmental Pollution, 310(2022), pp.
17. Wang, Y., Wang L., Li Z.T., Yang D., Xu J.M., and Liu X.M., *MgO-laden biochar enhances the immobilization of Cd/Pb in aqueous solution and contaminated soil.* Biochar, 3(2021), pp. 175–188
18. Xiang, J.X., Lin Q.T., Yao X.S., and Yin G.C., *Removal of Cd from aqueous solution by chitosan coated MgO-biochar and its in-situ remediation of Cd-contaminated soil*. Environmental Research, 195(2021), pp.
19. Yin, G.C., Tao L., Chen X.L., Bolan N.S., Sarkar B., Lin Q.T., and Wang H.L., *Quantitative analysis on the mechanism of Cd removal by MgCl-modified biochar in aqueous solutions*. Journal of Hazardous Materials, 420(2021), pp.
20. Xu, S.Z., Xing Y.H., Liu S., Luo X.S., Chen W.L., and Huang Q.Y., *Co-effect of minerals and Cd(II) promoted the formation of bacterial biofilm and consequently enhanced the sorption of Cd(II)*. Environmental Pollution, 258(2020), pp.

21. Sipos, P., Kis V.K., Balazs R., Tóth A., and Németh T., *Effect of pedogenic iron-oxyhydroxide removal on the metal sorption by soil clay minerals*. Journal of Soils and Sediments, 21(2021), pp. 1785–1799
22. Li, H., Ou J.Y., Wang X.D., Yan Z.G., and Zhou Y.Y., *Immobilization of soil cadmium using combined amendments of illite/smectite clay with bone chars*. Environmental Science and Pollution Research, 25(2018), pp. 20723–20731
23. Yang, Z.B., Guo W.Q., Cheng Z., Wang G.Y., Xian J.R., Yang Y.X., Liu L.X., and Xu X.X., *Possibility of using combined compost-attapulgite for remediation of Cd contaminated soil*. Journal of Cleaner Production, 368(2022), pp.
24. Gu, S.Q., Kang X.N., Wang L., Lichtfouse E., and Wang C.Y., *Clay mineral adsorbents for heavy metal removal from wastewater: a review*. Environmental Chemistry Letters, 17(2019), pp. 629–654
25. Xu, C.B., Qi J., Yang W.J., Chen Y., Yang C., He Y.L., Wang J., and Lin A.J., *Immobilization of heavy metals in vegetable-growing soils using nano zero-valent iron modified attapulgite clay*. Science of the Total Environment, 686(2019), pp. 476–483
26. Zhang, S.K., Gong X.F., Shen Z.Y., Yuan S.F., Jiang L., and Wang G.H., *Study on Remediation of Cd-Contaminated Soil by Thermally Modified Attapulgite Combined with Ryegrass*. Soil & Sediment Contamination, 29(2020), pp. 680–701
27. Xia, Y., Meng Y.H., Sun Y.T., Deng X.Y., Li K., Liu Z.G., and Miao W., *Facile one-step synthesis of attapulgite-hydrochar composite for in situ remediation of cadmium contaminated soils: Characterization, performance and mechanisms*. Journal of Environmental Chemical Engineering, 9(2021), pp.
28. Quan, G.X., Sui F.F., Wang M., Cui L.Q., Wang H., Xiang W., Li G.Y., and Yan J.L., *Mechanochemical modification of biochar-attapulgite nanocomposites for cadmium removal: Performance and mechanisms*. Biochemical Engineering Journal, 179(2022), pp.
29. Rizwan, M., Ali S., Rehman M.Z.U., Adrees M., Arshad M., Qayyum M.F., Ali L., Hussain A., Chatha S.A.S., and Imran M., *Alleviation of cadmium accumulation in maize (L.) by foliar spray of zinc oxide nanoparticles and biochar to contaminated soil*. Environmental Pollution, 248(2019), pp. 358–367
30. Rizwan, M., Noureen S., Ali S., Anwar S., Rehman M.Z.U., Qayyum M.F., and Hussain A., *Influence of biochar amendment and foliar application of iron oxide nanoparticles on growth, photosynthesis, and cadmium accumulation in rice biomass*. Journal of Soils and Sediments, 19(2019), pp. 3749–3759
31. Haider, F.U., Noor-ul-Ain, Khan I., Farooq M., Habiba, Cai L.Q., and Li Y.L., *Co-application of biochar and plant growth regulators improves maize growth and decreases Cd accumulation in cadmium-contaminated soil*. Journal of Cleaner Production, 440(2024), pp.
32. Wu, C., Dun Y., Zhang Z.J., Li M.L., and Wu G.Q., *Foliar application of selenium and zinc to alleviate wheat (L.) cadmium toxicity and uptake from cadmium-contaminated soil*. Ecotoxicology and Environmental Safety, 190(2020), pp.
33. Deng, S.W., Li P.R., Li Y.Z., Ran Z.X., Peng Y.X., Yang S.L., He H., Zhou K., and Yu J., *Alleviating Cd translocation and accumulation in soil-rice systems: Combination of foliar spraying of nano-Si or nano-Se and soil application of nano-humus*. Soil Use and Management, 37(2021), pp. 319–329

34. Wang, M., Mu C.Y., Lin X.Y., Ma W.Y., Wu H.T., Si D.F., Ge C.H., Cheng C., Zhao L.J., Li H.B., and Zhou D.M., *Foliar Application of Nanoparticles Reduced Cadmium Content in Wheat (L.) Grains via Long-Distance "Leaf-Root-Microorganism" Regulation*. Environmental Science & Technology, 58(2024), pp. 6900–6912
35. Guo, L., Chen A.T., Li C., Wang Y.J., Yang D., He N., and Liu M.D., *Solution chemistry mechanisms of exogenous silicon influencing the speciation and bioavailability of cadmium in alkaline paddy soil*. Journal of Hazardous Materials, 438(2022), pp.
36. Sun, S.Q., Zeng X., Gao Y., Zhang W., Zhou L.A., Zeng X.K., Liu W., Jiang Q., Jiang C.B., and Wang S.X., *Iron oxide loaded biochar/attapulgite composites derived shells as a novel bio-adsorbent for highly efficient removal of Cr(VI)*. Journal of Cleaner Production, 317(2021), pp.
37. Meng, W.S., Zhu F.N., Wang X.R., Guan S., Dou S., and Ndzelu B.S., *Contrasting effects of straw and straw-derived biochar application on soil organic matter and corn yield in a Chinese Mollisol*. Journal of Soils and Sediments, 23(2023), pp. 3843–3856
38. Wu, L.P., Zheng H.N., and Wang X.J., *Effects of soil amendments on fractions and stability of soil organic matter in saline-alkaline paddy*. Journal of Environmental Management, 294(2021), pp.
39. Jia, Y.H., Li J., Zeng X.B., Zhang N., Wen J., Liu J., Jiku M.A., Wu C.X., and Su S.M., *The performance and mechanism of cadmium availability mitigation by biochars differ among soils with different pH: Hints for the reasonable choice of passivators*. Journal of Environmental Management, 312(2022), pp.
40. Yuan, C.P., Gao B.L., Peng Y.T., Gao X., Fan B.B., and Chen Q., *A meta-analysis of heavy metal bioavailability response to biochar aging: Importance of soil and biochar properties*. Science of the Total Environment, 756(2021), pp.
41. Zhang, F., Hu B.J., Meng L., Pang M.L., Chen Y.Q., Song W.J., Feng Y.F., and Ma Y., *Appropriate biochar application methods can simultaneously mitigate Cd concentrations in different parts of soil and crops: A meta-analysis*. Soil Use and Management, 41(2025), pp.
42. Li, A.Y., Ye C.H., Jiang Y.H., and Deng H., *Enhanced removal performance of magnesium-modified biochar for cadmium in wastewaters: Role of active functional groups, processes, and mechanisms*. Bioresource Technology, 386(2023), pp.
43. Liu, Q.Z., Huang L.K., Chen Z.Q., Wen Z.Y., Ma L.Y., Xu S.A., Wu Y.J., Liu Y.R., and Feng Y., *Biochar and its combination with inorganic or organic amendment on growth, uptake and accumulation of cadmium on lettuce*. Journal of Cleaner Production, 370(2022), pp.
44. Lu, H.M., Qin S.T., Zhao J.Y., Pan P., Wang F.L., Tang S.D., Chen L.H., Akhtar K., and He B., *Silicon inhibits the upward transport of Cd in the first internode of different rice varieties in a Cd stressed farm land*. Journal of Hazardous Materials, 458(2023), pp.
45. De Caroli, M., Furini A., DalCorso G., Rojas M., and Di Sansebastiano G.P., *Endomembrane Reorganization Induced by Heavy Metals*. Plants-Basel, 9(2020), pp.
46. Liu, N., Huang X.M., Sun L.M., Li S.S., Chen Y.H., Cao X.Y., Wang W.X., Dai J.L., and Rinnan R., *Screening stably low cadmium and moderately high micronutrients wheat cultivars under three*

different agricultural environments of China. Chemosphere, 241(2020), pp.

47. Xing, W.Q., Liu H., Banet T., Wang H.S., Ippolito J.A., and Li L.P., *Cadmium, copper, lead and zinc accumulation in wild plant species near a lead smelter*. Ecotoxicology and Environmental Safety, 198(2020), pp.
48. Liu, C.P., Li F.B., Luo C.L., Liu X.M., Wang S.H., Liu T.X., and Li X.D., *Foliar application of two silica sols reduced cadmium accumulation in rice grains*. Journal of Hazardous Materials, 161(2009), pp. 1466–1472
49. Han, J.N., Wu D.H., Yang J.H., Shi Y., Abid G., Wang L.J., and Li Z.G., *A biochar-based amendment improved cadmium (Cd) immobilization, reduced its bioaccumulation, and increased rice yield*. Frontiers in Environmental Science, 12(2024), pp.

Figures

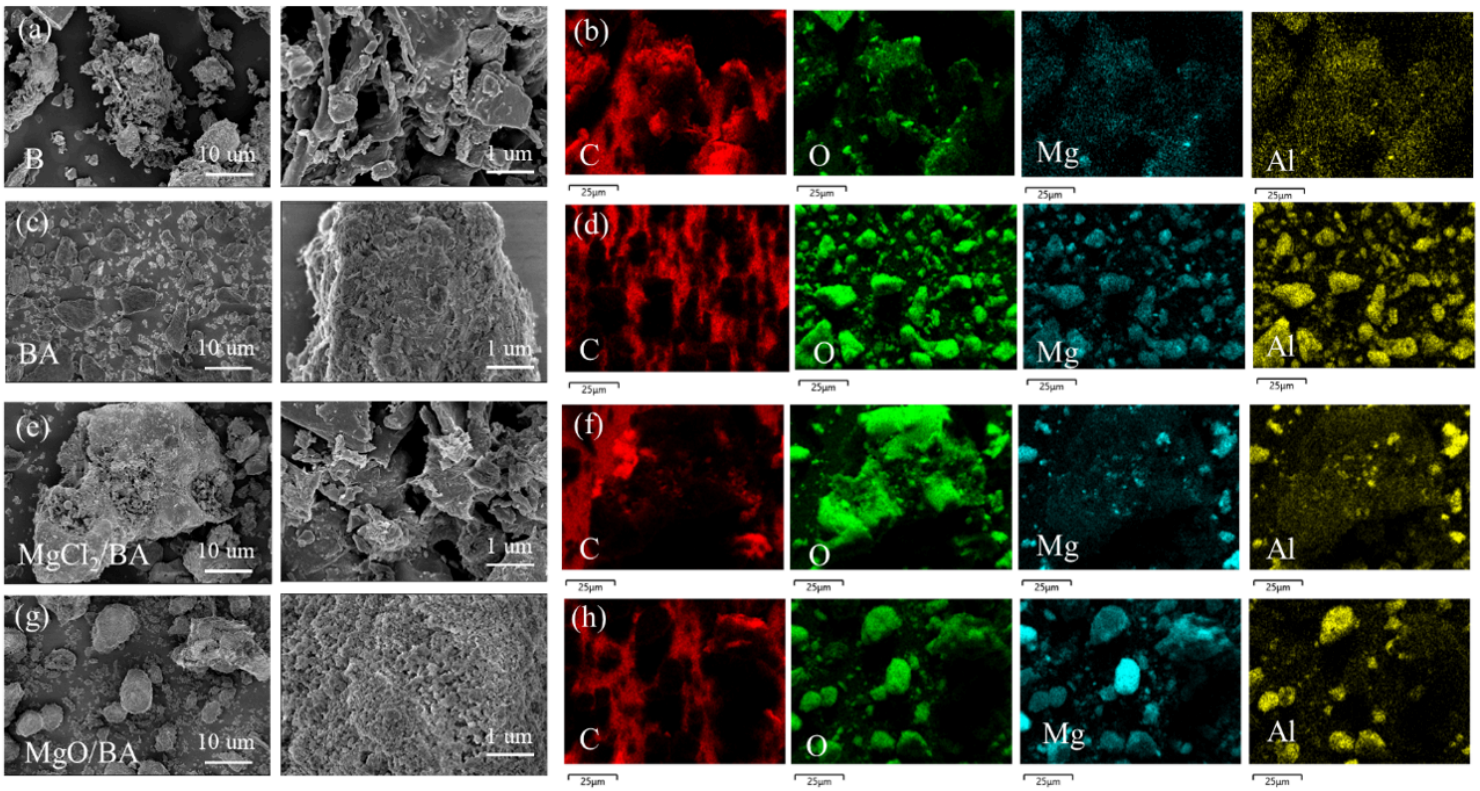


Figure 1

SEM and EDS-mapping images of different materials

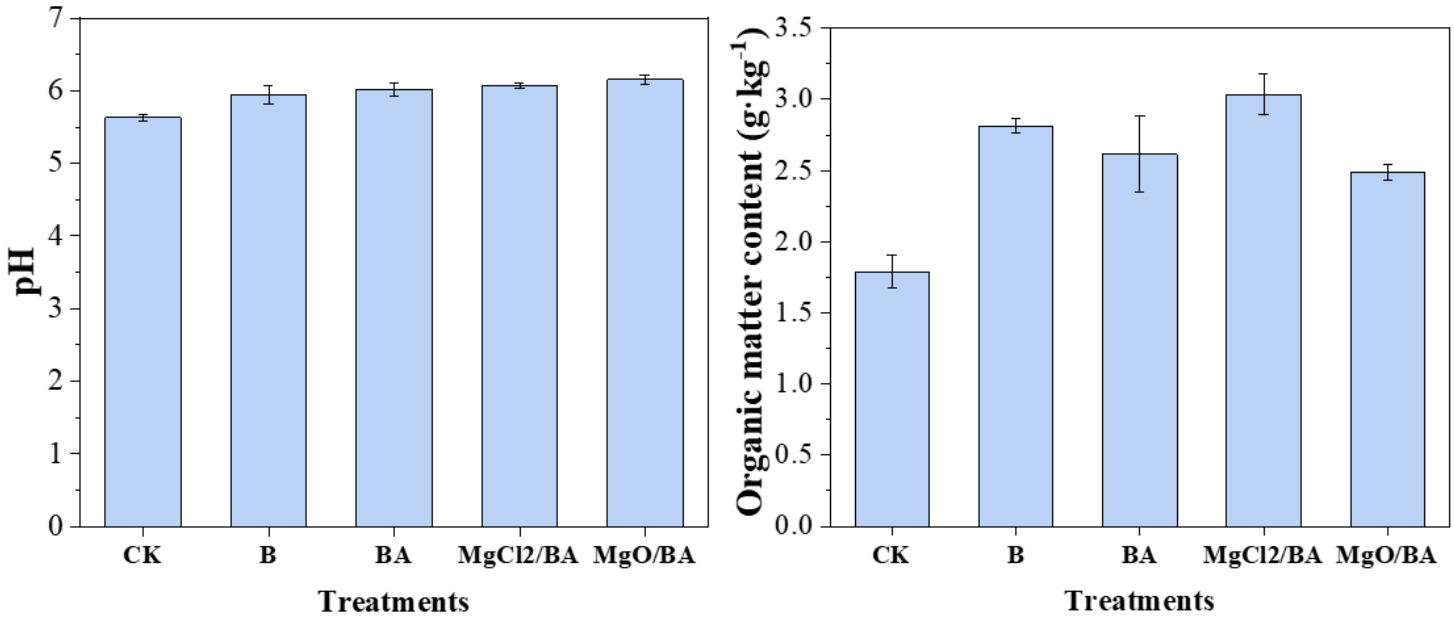


Figure 2

Soil pH and soil organic matter content of different treatments

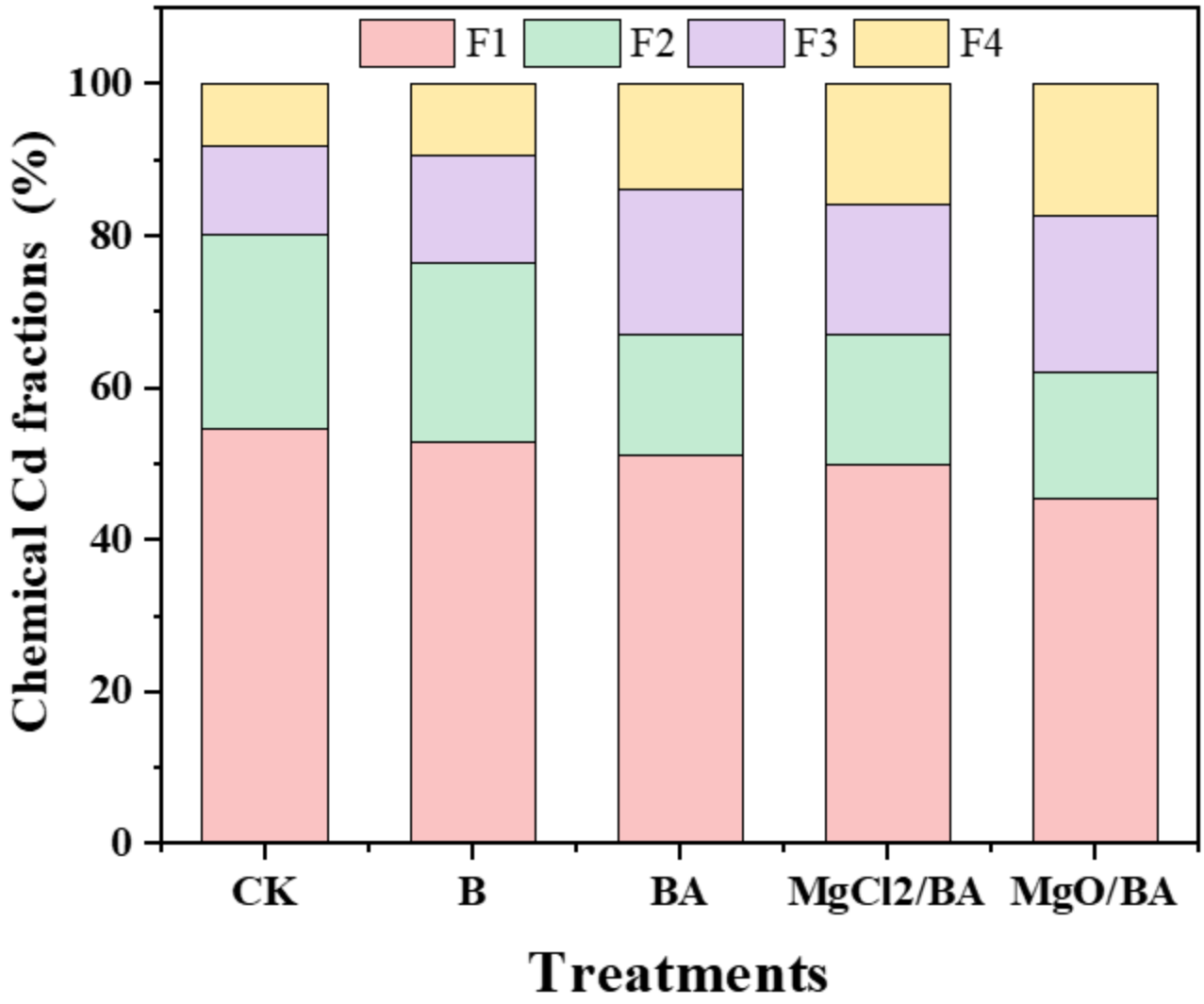


Figure 3

Content of different forms of Cd in soils under different treatments (F1: acid-soluble form; F2: reducible form; F3: oxidizable form; F4: residual form)

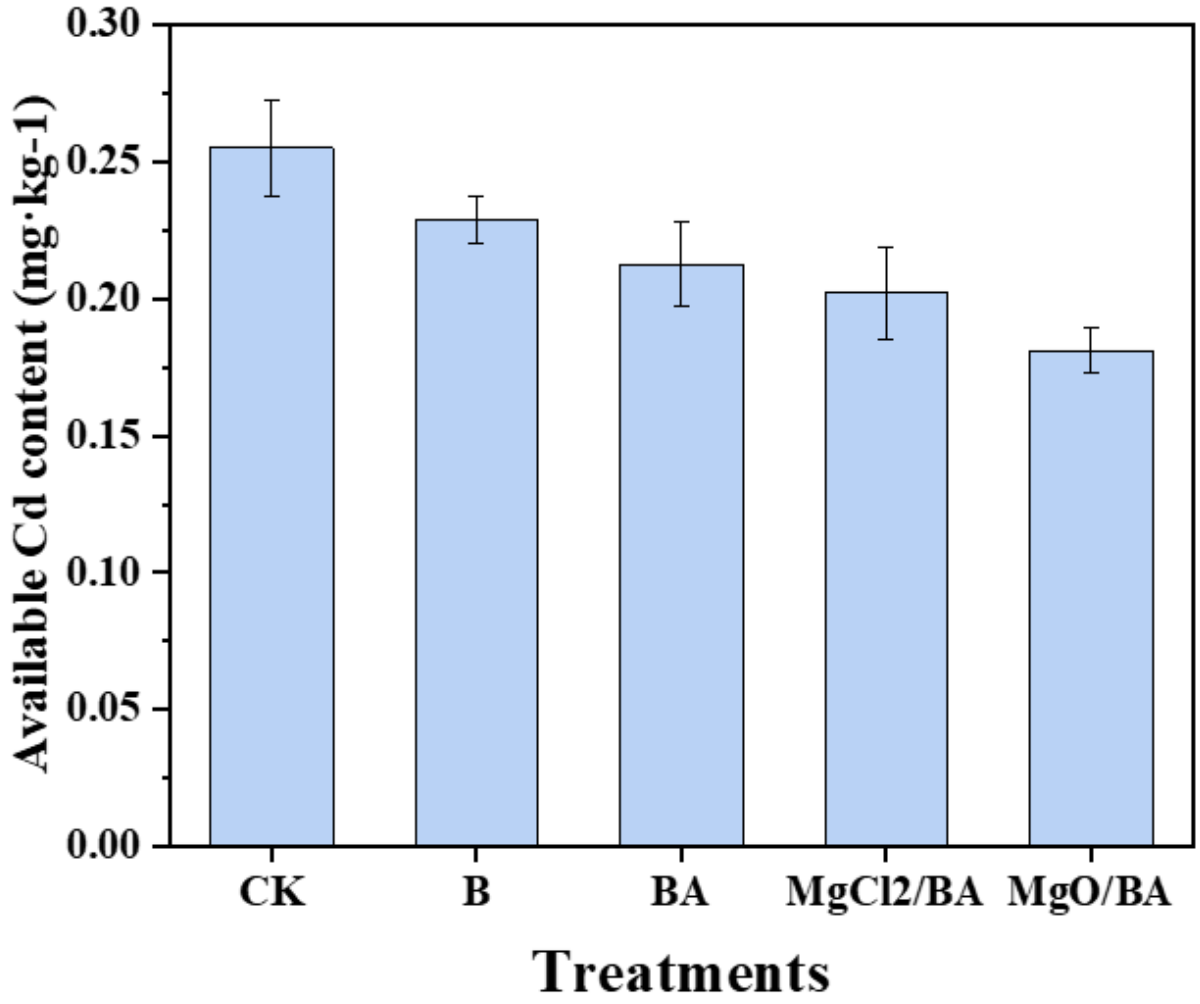


Figure 4

Available Cd Content in soil of different treatments

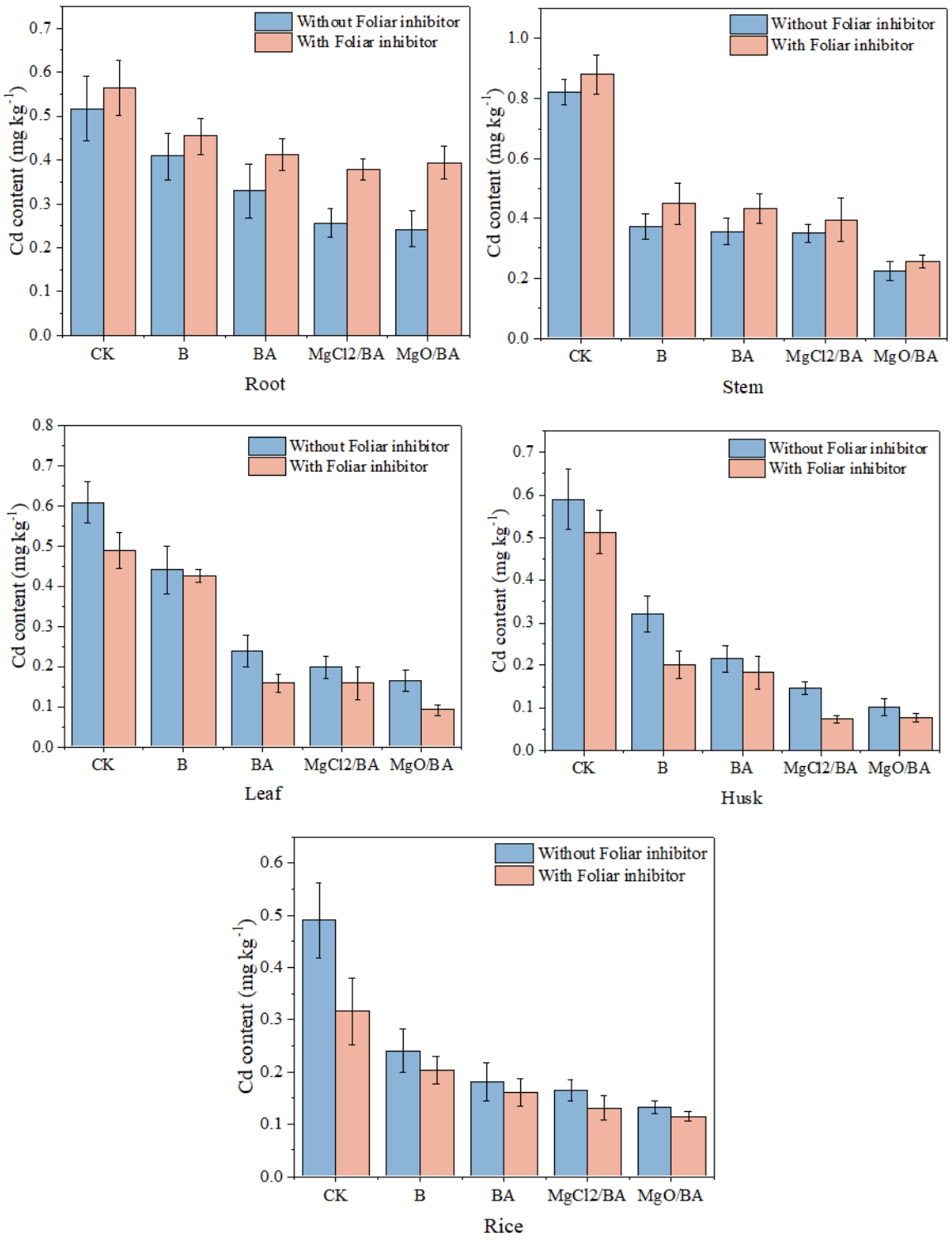


Figure 5

Cadmium content in roots, stems, leaves, husks and grains of rice of different treatments

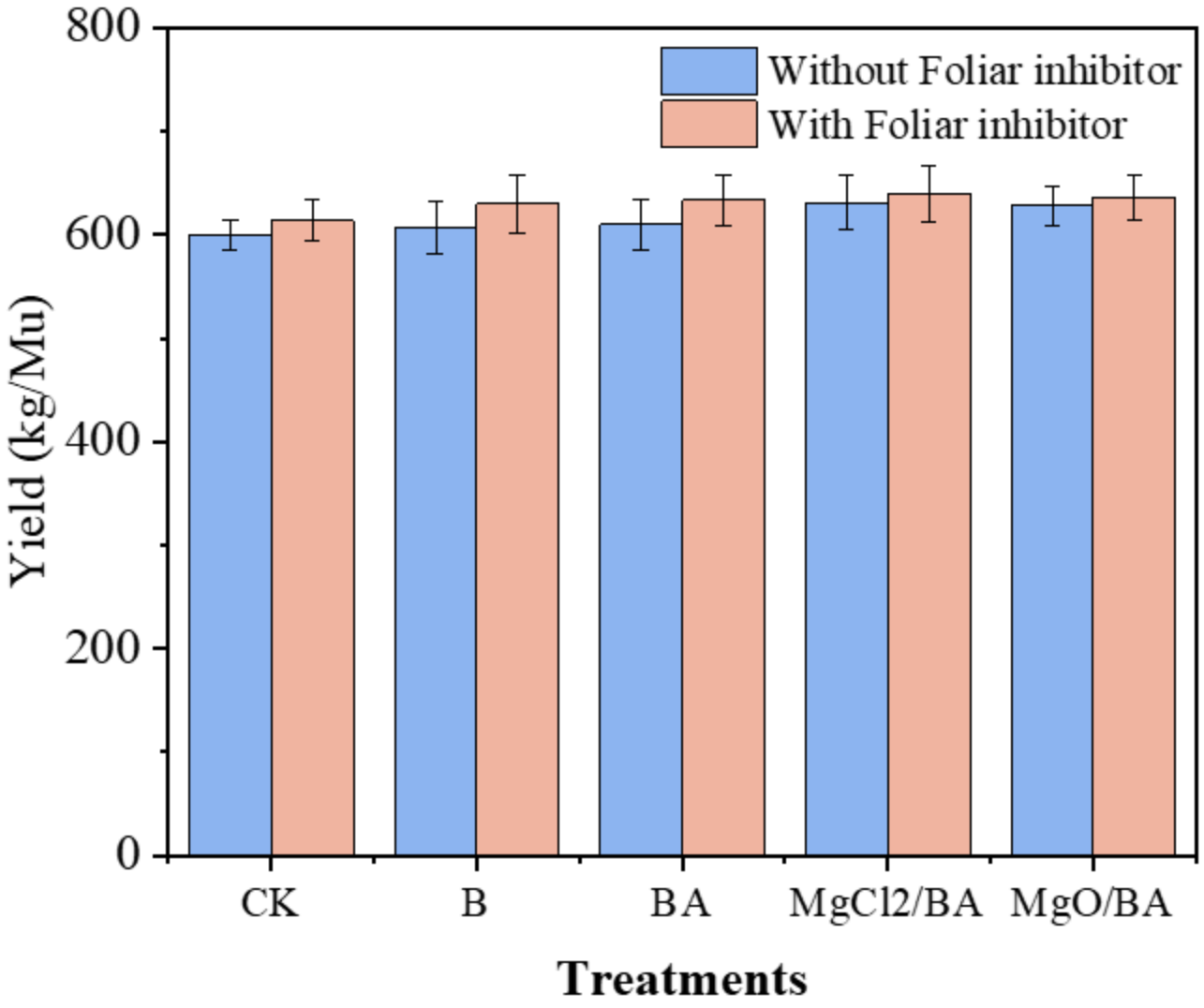


Figure 6

Rice yield under different treatments