



Wood Chip Biochar–Sepiolite Composite Reduces Cadmium Accumulation in Maize

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ABSTRACT: This study aimed to evaluate the effectiveness of a composite material consisting of wood chip biochar (WCB) and sepiolite in reducing cadmium (Cd) uptake, accumulation, and translocation in maize cultivated in Cd-contaminated soil in Vietnam. A field experiment was conducted using three maize varieties (LVN10, NK7328, and CP511) under eight treatment conditions, including a control (CK), individual applications of WCB or Sep, and combined WCB/Sep treatments at different ratios. Cadmium concentrations in roots, stems, leaves, and grains were determined using atomic absorption spectroscopy (AAS), while the bioconcentration factor (BCF) and translocation factor (TF) were calculated to assess Cd accumulation and transport within the plants. The results showed that Cd accumulated predominantly in the roots, followed by leaves, stems, and the lowest levels in grains. Individual application of WCB or Sep only resulted in limited reductions in Cd accumulation, whereas the combined treatments exhibited more pronounced effects. Among them, the W2S2 treatment (0.2% WCB + 0.6% Sep) demonstrated the highest effectiveness across most parameters, significantly reducing Cd concentrations in roots, stems, leaves, and grains compared with the control. The BCF values decreased by up to 36.1% in LVN10 and 45.0% in CP511, while all TF values remained below 1, indicating restricted Cd translocation into grains. These findings demonstrate that the WCB/Sep composite has strong potential as an effective immobilization strategy to reduce the bioavailability of Cd in soil, thereby improving crop safety and supporting the sustainable management of heavy metal-contaminated agricultural land.

KEYWORDS: Cadmium, biochar, sepiolite, maize, heavy metal, accumulation reduction.

1. Introduction

Cadmium (Cd) is a toxic heavy metal characterized by its long-term persistence in the environment, high potential for bioaccumulation, and serious adverse effects on human health and ecosystems [1, 2]. Sources of Cd contamination in agricultural soils include the application of chemical fertilizers, pesticides, contaminated irrigation water, industrial waste, mining activities, and atmospheric deposition [2]. Once present in soil, Cd can be absorbed by plant

roots and translocated to aboveground tissues, thereby entering the food chain and posing significant risks to human health [3]. Prolonged exposure to Cd has been associated with kidney damage, liver dysfunction, neurological disorders, osteoporosis, and an increased risk of cancer [1].

Maize is one of the most important food crops in Vietnam, playing a crucial role in food security, animal feed production, and the processing industry. However, maize has the capacity to absorb and accumulate heavy metals from soil, particularly in contaminated areas, which can negatively affect plant growth, yield, and crop quality [4]. Meanwhile, Vietnam is facing increasing risks of soil environmental contamination [5, 6]. Cadmium are initially taken up by roots via metal transporters, such as ZIP and NRAMP proteins, and subsequently translocated to stems, leaves, and grains through the xylem and phloem [7]. Although roots generally retain a considerable proportion of absorbed Cd, a fraction can still be transported to edible tissues, particularly grains, thereby entering the food chain. The accumulation of heavy metals in maize not only impairs plant growth, photosynthesis, and grain quality but also poses serious risks to human health [1, 2]. Therefore, developing effective strategies to reduce Cd uptake by crops has become an urgent priority.

In recent years, environmentally friendly immobilization materials have been considered promising approaches for reducing the bioavailability of heavy metals in soil. Biochar (BC), with its highly porous structure, large specific surface area, and abundant oxygen-containing functional groups, provides favorable conditions for the adsorption and immobilization of heavy metal ions [8, 9]. Numerous studies have demonstrated the effectiveness of BC in reducing Cd mobility in soil. Wang et al. (2022) reported that the application of 1% wood-derived biochar reduced bioavailable Cd in paddy soil by 42.9% [10]. Similarly, Yu et al. (2021) found that the addition of 2% tobacco-straw biochar decreased exchangeable Cd in red soil from 40% to 23%, resulting in significantly lower Cd accumulation in tobacco leaves [11]. In addition, Sep), a natural clay mineral with a distinctive fibrous chain-layer structure, large surface area, and strong adsorption capacity for heavy metals, has also shown promising remediation potential. Sep treatment reduced acid-soluble Cd in wastewater-irrigated soil by 42.8% and decreased Cd concentrations in spinach roots and shoots by 26.2% and 30.6%, respectively [12]. Li et al. (2019) also reported that Sep amendment reduced bioavailable Cd in slightly alkaline contaminated soil by up to 65.73% [13]. Previous studies have also applied sepiolite for the remediation of heavy metal-contaminated soils and reported promising results [14].

Nevertheless, the individual application of immobilization materials does not always achieve optimal remediation efficiency. In some cases, inappropriate use may adversely alter soil physicochemical properties, thereby affecting crop growth and soil quality [15]. Current research trends increasingly focus on combining different immobilization materials to exploit synergistic effects, enhance heavy metal stabilization, and simultaneously improve soil quality [16, 17]. Recent studies have demonstrated that biochar–clay mineral composites can improve Cd immobilization through synergistic adsorption, ion exchange, and surface complexation mechanisms [18]. Recently, Zeng et al. evaluated a biochar–sepiolite composite for mitigating cadmium and lead accumulation in soils cultivated with 29 maize varieties in China [16]. The sepiolite–biochar composite exhibited superior Cd immobilization efficiency (67.89%), while significantly improving soil structural stability, fertility, and biological activity [19]. However, limited information is available regarding the performance of wood chip biochar–sepiolite

composites under Vietnamese agricultural conditions, where soil properties, climate, and crop management practices differ substantially from those reported in previous studies. Furthermore, comparative assessments among maize varieties with different genetic backgrounds remain scarce. Therefore, this study aimed to evaluate the effectiveness of a wood chip biochar–sepiolite composite in reducing Cd uptake, accumulation, and translocation in three widely cultivated maize varieties in Vietnam. The findings provide new evidence for the practical application of composite immobilization materials in improving crop safety and managing Cd-contaminated agricultural soils in Vietnam.

2. Materials and Methods

2.1. Material preparation.

WCB was prepared using a slow pyrolysis method. Wood chips were collected from a woodworking facility in Hanoi, Vietnam, dried at 40 °C. Previous studies have shown that biochar produced at temperatures ranging from 500 to 700 °C generally exhibits a larger specific surface area, higher porosity, greater aromatic carbon content, and improved stability compared with biochar produced at lower pyrolysis temperatures [10]. Therefore, biochar was produced at 600 °C for 2 h in this study to optimize its physicochemical properties and enhance its heavy metal adsorption and immobilization capacity. Sepiolite was purchased from Sigma–Aldrich. To prepare the WCB/Sep composite material, WCB and Sep were ground separately and sieved through a 20-mesh sieve. The two materials were then mechanically mixed using a stirrer at 300 rpm at WCB:Sep mass ratios of 1:2, 1:1, and 2:5. The resulting mixtures were stored in sealed containers at room temperature until use. Three maize hybrids (LVN10, CP511, and NK7328) were provided by the Vietnam National University of Agriculture Seed Center. These hybrids were selected because they are widely cultivated in Vietnam due to their vigorous growth, broad adaptability, and high grain yields ranging from approximately 8 to 14 t ha⁻¹ [20]. The use of these varieties allowed the evaluation of WCB/Sep effectiveness across commercially important maize genotypes with different agronomic characteristics.

2.2. Experimental design.

The experiment was conducted at the experimental field of the Vietnam National University of Agriculture to evaluate the effectiveness of a composite material derived from WCB and sepiolite in reducing cadmium (Cd) accumulation in maize grown under Cd-contaminated soil conditions in Vietnam. Three maize varieties, namely LVN10, NK7328, and CP511, were selected for the study. The experimental soil was artificially contaminated with Cd prior to treatment application. Each treatment plot measured 3 m × 4 m (12 m²) and was arranged in a randomized complete block design with three replicates. Approximately 2,500 kg of soil was contained within each experimental plot to a cultivation depth of 20 cm. The soil amendments were thoroughly mixed with the topsoil layer before sowing. The initial physicochemical properties of the soil included a pH of 7.58, dissolved organic carbon (DOC) content of 84.32 mg/kg, electrical conductivity (EC) of 215.14 μS·cm⁻¹, and total Cd concentration of 5.30 mg/kg. This Cd concentration exceeded the permissible limit for agricultural soils according to QCVN 03:2023/BTNMT (4 mg/kg), indicating that the soil was Cd-contaminated. The experiment consisted of four treatment categories: control without amendment (CK), WCB alone (W), sepiolite alone (S), and the WCB/Sep composite material (WS). The amendments

were thoroughly mixed with the soil before sowing to ensure uniform distribution throughout the cultivation medium. Maize seeds were planted and cultivated under the same agronomic management conditions to minimize variation among treatments. The experiment was conducted from May to August 2025 under typical summer conditions in northern Vietnam, with average temperatures of 27–33 °C and relative humidity of 75–85%. Eight treatment combinations (Table 1), each with three replicates, were established at the beginning of the growing season. Maize was planted at a spacing of 70 cm × 25 cm, corresponding to a density of approximately 57,000 plants/ha. All treatments received the same fertilization regime following local agronomic recommendations: 180 kg N/ha, 90 kg P₂O₅/ha, and 90 kg K₂O/ha. Phosphorus was applied as a basal fertilizer, whereas nitrogen and potassium were applied in three split applications during the growing season. Irrigation was performed as required to maintain soil moisture at approximately 60–70% of field capacity and to avoid water stress during plant growth. During the experimental period, maize was grown under natural climatic conditions. The average air temperature ranged from 27 to 33 °C, relative humidity ranged from 75 to 85%, and total rainfall was approximately 450–600 mm during the growing season. Each treatment included the three maize varieties (LVN10, NK7328, and CP511). At maturity, maize plants were harvested, and the roots, stems, leaves, and grains were separated, air-dried, ground, and sieved for further analysis.

Table 1. Experimental treatments.

No.	Treatment
1	Control treatment (CK)
2	0.1% WCB (W1)
3	0.2% WCB (W2)
4	0.3% sepiolite (S1)
5	0.6% sepiolite (S2)
6	0.1% WCB + 0.2% sepiolite (W1S1)
7	0.2% WCB + 0.3% sepiolite (W2S1)
8	0.2% WCB + 0.6% sepiolite (W2S2)

2.3. Cadmium analysis.

At the end of the experiment, soil and plant samples were collected to determine Cd concentrations. Soil samples were air-dried, impurities were removed, and the samples were finely ground and passed through a 0.15 mm sieve prior to analysis. Plant samples were thoroughly washed with tap water and rinsed with distilled water to remove dust and surface-adhered metals, then oven-dried at 70 °C to constant weight, finely ground, and stored in sealed bags until analysis. The samples were digested using the wet acid digestion method with an HNO₃–HClO₄ mixture. Cadmium concentrations in the digested solutions were determined using atomic absorption spectroscopy (AAS). The results were expressed as mg/kg dry weight. To ensure analytical reliability, blank samples, duplicate samples, and certified reference materials were analyzed simultaneously under the same experimental.

2.4. Data analysis.

The data were compiled and analyzed using descriptive statistical methods. Results were expressed as mean ± standard deviation (SD) based on three replicates. Differences among experimental treatments were evaluated using one-way analysis of variance (one-way ANOVA). When significant differences were detected, Duncan's multiple range test was applied to compare treatment means at a significance level of $p < 0.05$. The accumulation and

transport of Cd in maize grain were calculated using the bioconcentration factor (BCF) (Eq.1) and translocation factor (TF) (Eq.2) [21] as follows:

$$\text{BCF} = \frac{C_m}{C_r} \quad (1)$$

$$\text{TF} = \frac{C_m}{(C_s + C_l)} \quad (2)$$

Where: C_m ($\text{mg} \cdot \text{kg}^{-1}$) was the Cd content of maize grain; C_r ($\text{mg} \cdot \text{kg}^{-1}$) was the soil total Cd content, and C_s ($\text{mg} \cdot \text{kg}^{-1}$) was the Cd content of maize stems; C_l ($\text{mg} \cdot \text{kg}^{-1}$) was the Cd content of maize leaves.

3. Results and Discussion

3.1. Cadmium accumulation in roots.

The results showed that the CK exhibited the highest Cd concentrations in the roots of all three maize varieties, reaching approximately 0.50 mg/kg in LVN10, 0.40 mg/kg in NK7328, and 0.39 mg/kg in CP511. This indicates that in the absence of soil amendments, Cd remained in more bioavailable forms, resulting in greater accumulation in the root system. Treatments using individual amendments, including WCB (W1, W2) or sepiolite (S1, S2), generally reduced root Cd concentrations compared with CK, although the effectiveness varied among maize varieties (Figure 1). In LVN10, W2 reduced Cd more effectively than W1, while S2 performed better than S1, with the reduction being statistically significant compared with the control. A similar trend was observed in NK7328, where S2 resulted in lower Cd concentrations than S1, and W2 was more effective than W1; however, these differences were not statistically significant. In CP511, individual amendment treatments only produced slight reductions in root Cd concentrations, with no statistically significant differences compared with CK. These findings suggest that when applied individually, the Cd reduction efficiency of the materials depended strongly on the application rate, and higher doses did not always result in substantially improved performance. Notably, the combined WCB/Sep treatments showed greater effectiveness in reducing Cd accumulation in roots compared with individual amendments. In LVN10, the W2S2 treatment reduced root Cd to the lowest level, approximately 0.31 mg/kg, significantly lower than CK, W1, S1, and S2, with a statistically significant difference compared with the control. In NK7328, W2S2 was also the most effective treatment, reducing root Cd to approximately 0.24 $\text{mg} \cdot \text{kg}^{-1}$, with a significant difference relative to CK. In CP511, W2S1 achieved the lowest Cd concentration, approximately 0.30 mg/kg, followed by W2S2 and W1S1; among these, W2S1 and W2S2 showed statistically significant reductions compared with the control ($p < 0.05$). Although S2 and W2 showed lower root Cd concentrations than S1 and W1, respectively, the differences among CK, W1, W2, S1, and S2 were not statistically significant ($p > 0.05$), indicating that the observed reductions were insufficient to overcome experimental variability. These results indicate that combining biochar and sepiolite enhances Cd immobilization in soil more effectively than using either material alone. Among the combined treatments, W2S2 generally showed the best performance for LVN10 and NK7328, whereas W2S1 appeared more suitable for CP511. The W1S1 treatment showed intermediate effectiveness, generally lower than W2S2 or W2S1, and did not

consistently produce statistically significant differences. Overall, the combined WCB/Sep treatments were more effective in reducing Cd accumulation in maize roots than the individual application of WCB or sepiolite.

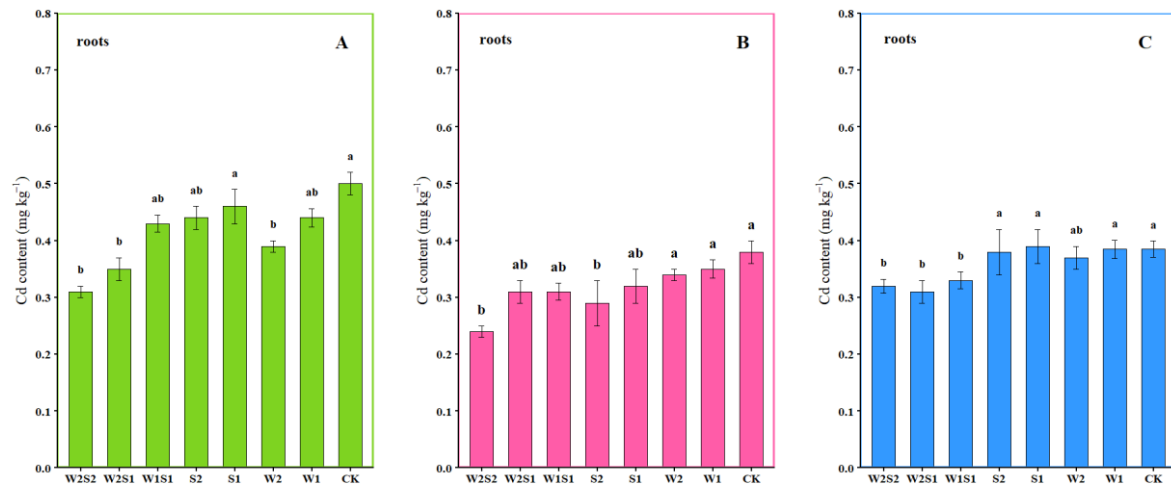


Figure 1. Cadmium accumulation in maize roots (A. LVN10, B. NK7328, and C. CP511). Different lowercase letters above bars indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$) following one-way ANOVA.

3.2. Cadmium accumulation in stems.

Cadmium concentrations in the stems were lower than those in the roots, indicating that a portion of the absorbed Cd was retained in the root system, thereby limiting its translocation to aboveground plant tissues. In all three maize varieties, the control treatment (CK) consistently exhibited among the highest Cd concentrations in stems (Figure 2). Treatments involving individual applications of WCB (W1, W2) or sepiolite (S1, S2) showed only limited effectiveness in reducing Cd accumulation. In LVN10, individual treatments generally resulted in slight reductions in stem Cd concentrations compared with CK, but most differences were not pronounced; among these, W1 and S2 were less effective than the combined treatments. In NK7328, W2S2 demonstrated the greatest reduction in Cd accumulation, whereas the individual amendments showed no significant differences compared with CK. A similar pattern was observed in CP511, where single-material treatments only slightly reduced stem Cd concentrations and did not result in statistically significant differences relative to the control. These findings suggest that individual applications had limited ability to restrict Cd translocation from roots to stems. In contrast, the combined WCB/Sep treatments exhibited more pronounced effects. In LVN10, the W2S2 and W2S1 treatments produced the lowest Cd concentrations in stems, approximately 0.23–0.24 mg/kg, significantly lower than CK (0.33 mg/kg), with statistically significant differences. In NK7328, W2S2 remained the most effective treatment, reducing stem Cd concentrations to approximately 0.18 mg/kg compared with around 0.30 mg/kg in the control, demonstrating a clear and statistically significant reduction. In CP511, a similar trend was observed, with W2S2 and W2S1 resulting in the lowest Cd concentrations, significantly lower than CK. These results indicate that the combination of biochar and sepiolite not only reduced Cd uptake at the root level but also effectively restricted Cd translocation to the stem. Overall, the combined WCB/Sep treatments were more effective in reducing Cd accumulation in maize stems than the individual application of biochar or sepiolite. This suggests that the composite material can reduce Cd

mobility in soil while simultaneously limiting Cd transport from roots to stems, thereby lowering the risk of Cd accumulation in aboveground plant tissues.

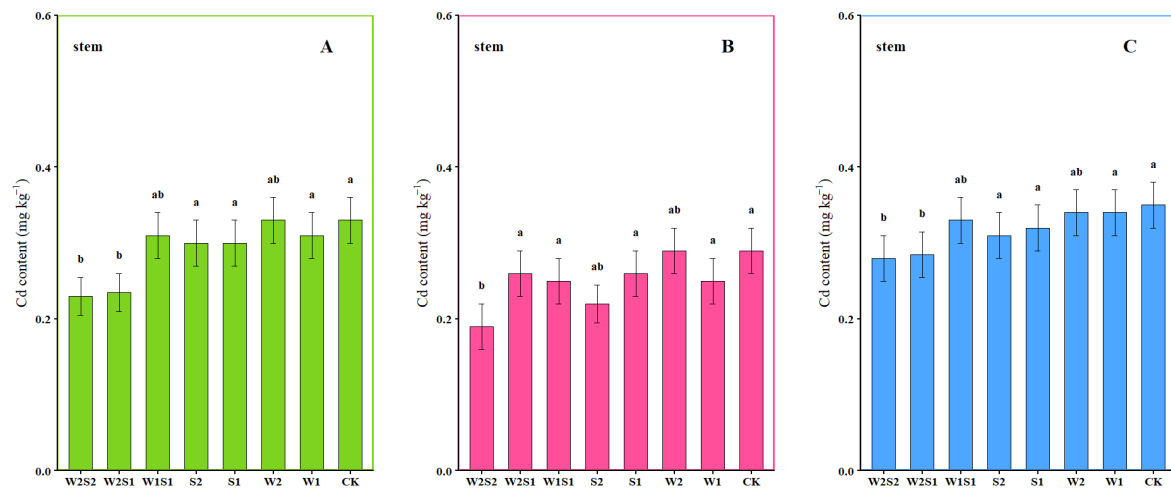


Figure 2. Cadmium accumulation in maize stems (A. LVN10, B. NK7328, and C. CP511). Different lowercase letters above bars indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$) following one-way ANOVA.

3.3. Cadmium accumulation in grains.

Individual applications of WCB (W1, W2) or sepiolite (S1, S2) reduced Cd concentrations in maize grains to varying extents depending on the maize variety (Figure 3). In LVN10, the individual amendment treatments only slightly reduced grain Cd concentrations compared with the control (CK), with S2 showing a somewhat better reduction trend than S1; however, the overall effect remained limited. In NK7328, Cd concentrations under the individual treatments were generally close to those observed in CK, with most differences not being statistically significant.

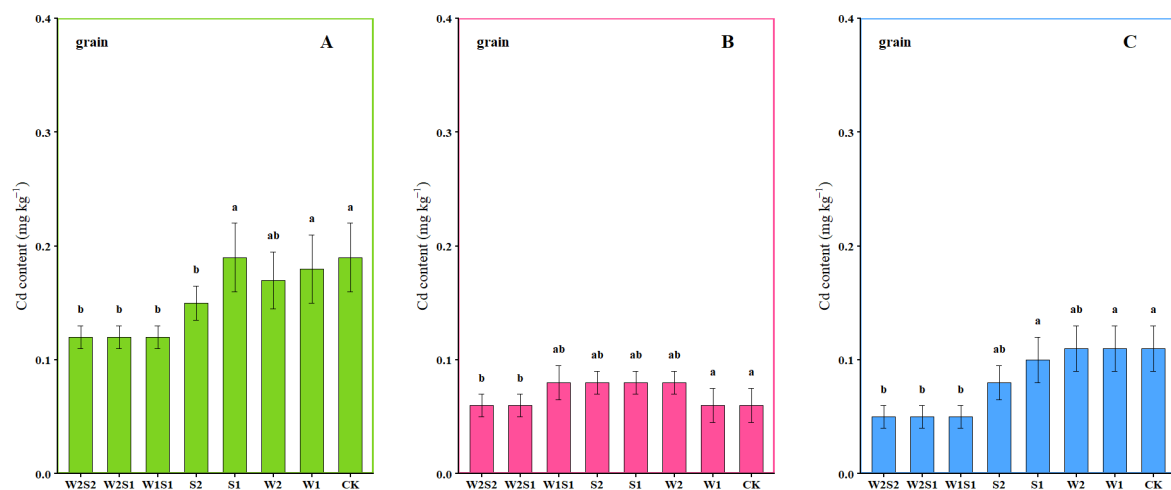


Figure 3. Cadmium accumulation in maize grains (A. LVN10, B. NK7328, and C. CP511). Different lowercase letters above bars indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$) following one-way ANOVA.

A similar pattern was observed in CP511, where single-material applications only resulted in modest reductions in grain Cd concentrations. These findings indicate that the individual application of either amendment was insufficient to effectively control Cd

translocation into maize grains. In contrast, the combined WCB/Sep treatments exhibited more pronounced effects. In LVN10, the W2S2, W2S1, and W1S1 treatments resulted in the lowest grain Cd concentrations (approximately 0.12–0.13 mg/kg), significantly lower than CK (0.19 mg/kg), with statistically significant differences. In NK7328, a similar trend was observed, with W2S2 and W2S1 producing the lowest Cd concentrations, significantly reduced compared with the control. In CP511, the W2S2, W2S1, and W1S1 treatments also resulted in lower grain Cd concentrations than CK, with W2S2 showing the greatest effectiveness and a statistically significant difference. These results demonstrate that the combined application of biochar and sepiolite effectively restricts Cd translocation from soil into maize grains.

3.4. Cadmium accumulation in leaves.

Figure 4 shows that Cd concentrations accumulated in maize leaves ranged from 0.32 to 0.43 mg/kg, depending on the maize variety and treatment applied. In the LVN10 variety, the control treatment (CK) recorded the highest Cd concentration, approximately 0.43 mg/kg, while all amendment treatments reduced Cd accumulation to some extent. The lowest concentrations were observed in the combined treatments W2S2 and W2S1, reaching approximately 0.36–0.37 mg/kg; however, these reductions were not statistically significant. For the NK7328 variety, CK showed a Cd concentration of approximately 0.38 mg/kg, whereas W2S2 resulted in the lowest value, around 0.33 mg·kg⁻¹, with a statistically significant difference compared with the control. Other combined treatments, such as W2S1 and W1S1, also showed a decreasing trend, with Cd concentrations of approximately 0.34–0.35 mg/kg, although these differences were not statistically significant. In contrast, the individual amendment treatments ranged from 0.37 to 0.39 mg/kg, remaining close to the control level. A similar pattern was observed in the CP511 variety, where the control treatment recorded approximately 0.39 mg/kg, while W2S2 reduced Cd concentration to approximately 0.33 mg/kg, showing a statistically significant difference. The W2S1 and W1S1 treatments resulted in Cd concentrations of approximately 0.35–0.36 mg/kg, lower than the control but without clear statistical significance. Notably, the W2 treatment recorded the highest Cd concentration, approximately 0.42 mg/kg, indicating that the individual application of biochar at this rate was ineffective in reducing Cd accumulation in the leaves of the CP511 variety.

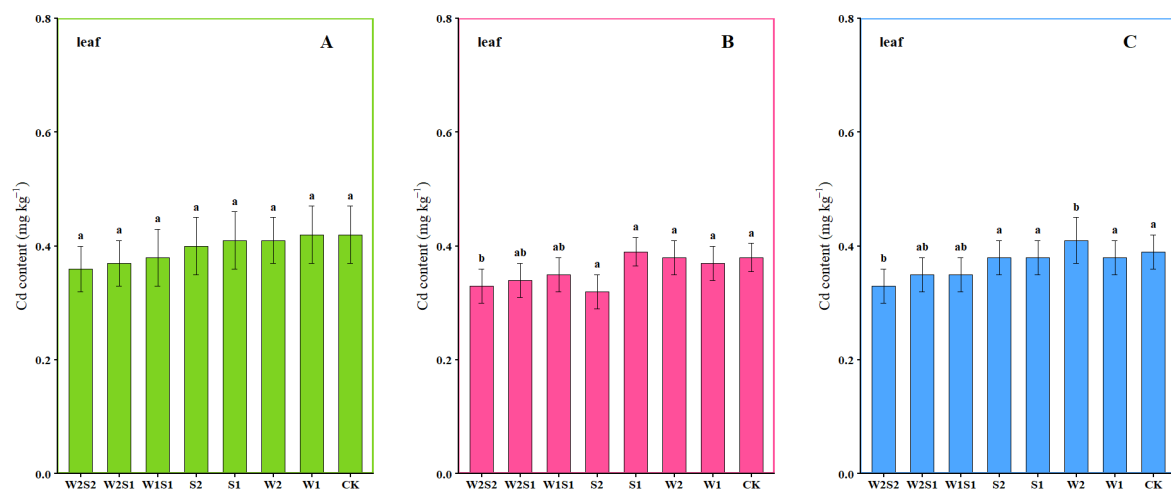


Figure 4. Cadmium accumulation in maize leaves (A. LVN10, B. NK7328, and C. CP511). Different lowercase letters above bars indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$) following one-way ANOVA.

3.5. Bioconcentration factor and translocation factor of Cd in maize plants.

The bioconcentration factor (BCF) and translocation factor (TF) for Cd in maize grains were calculated to evaluate the accumulation and transport behavior of Cd in maize under different treatment conditions. Compared with the control (CK), the BCF values from soil to grain decreased by 11.1%–36.1% in the LVN10 variety, showed only slight variation or a maximum reduction of approximately 27.3% in NK7328, and decreased by 5.0%–45.0% in CP511. Notably, the combined amendment treatments exhibited more pronounced reductions in BCF compared with the individual materials. Specifically, the W2S2 treatment resulted in the greatest reduction in BCF for LVN10 (36.1%), while both W2S1 and W2S2 showed the highest effectiveness in CP511, with reductions of approximately 45.0%. In NK7328, the differences among treatments were relatively small due to the inherently low baseline BCF values; however, the combined treatments still maintained lower BCF values than most individual amendment treatments. The TF values from stem to grain ranged from 0.39 to 0.61 for LVN10, 0.20 to 0.37 for NK7328, and 0.20 to 0.32 for CP511, with all values remaining below 1. This indicates that Cd translocation to grains was restricted rather than strongly accumulated in the reproductive organs. Among the treatments, W1S1 showed the lowest TF value in LVN10 (0.39), whereas W2S1 and W2S2 produced the lowest TF values in CP511 (0.21). In NK7328, TF values remained consistently low across treatments, suggesting relatively stable intrinsic control of Cd translocation in this variety. The differences in BCF and TF among LVN10, NK7328, and CP511 indicate that Cd uptake and translocation are strongly genotype-dependent. NK7328 appeared to have a greater capacity for root retention and restriction of Cd transport to grains, whereas LVN10 showed relatively higher Cd accumulation, possibly due to differences in metal transporter activity, root cell wall binding, and vacuolar sequestration mechanisms [7, 16]. Overall, the combined application of biochar and sepiolite, particularly the W2S2 treatment, demonstrated superior effectiveness in reducing Cd accumulation in maize grains through lowering BCF while maintaining low TF values. These findings suggest that the WCB/sepiolite composite material has strong potential as an effective immobilization strategy for limiting Cd accumulation and translocation in maize cultivated on contaminated soils.

The observed varietal differences in BCF values are consistent with previous studies reporting substantial variation in Cd accumulation among maize genotypes. Zeng et al. (2025) reported that cultivars such as NZY801 and WG1790 exhibited considerably higher Cd bioconcentration capacities than other maize varieties, indicating genotype-dependent Cd uptake behavior [16]. In the present study, LVN10 showed higher baseline BCF values than NK7328 and CP511 (Table 2), suggesting a relatively greater capacity for Cd accumulation. However, unlike the findings of Zeng et al. (2025) [16], where sepiolite alone increased Cd BCF in some cultivars (e.g., QR47 and SY3899), the application of sepiolite alone in the present study either reduced or only slightly altered BCF values relative to the control. This discrepancy may be related to differences in maize genotype, soil properties, Cd contamination levels, and amendment application rates. Nevertheless, both studies consistently demonstrated that combined biochar–sepiolite treatments were more effective than individual amendments in reducing Cd accumulation. The reduction in BCF observed under WCB/ sepiolite treatments in this study supports previous findings that biochar provides abundant adsorption sites and

increases soil pH, while sepiolite contributes additional cation exchange and adsorption capacity, thereby decreasing Cd mobility and bioavailability in soil [16, 22].

Table 2. Bioconcentration factor and translocation factor values of Cd in maize grains under different treatments.

Treatment	LVN10		NK7328		CP511	
	BCF	TF	BCF	TF	BCF	TF
CK	0.036	0.576	0.011	0.200	0.020	0.300
W1	0.034	0.581	0.012	0.260	0.020	0.318
W2	0.032	0.500	0.015	0.276	0.019	0.303
S1	0.036	0.613	0.016	0.327	0.018	0.306
S2	0.028	0.500	0.016	0.370	0.016	0.283
W1S1	0.023	0.387	0.016	0.340	0.012	0.203
W2S1	0.023	0.500	0.012	0.250	0.011	0.214
W2S2	0.023	0.522	0.012	0.361	0.011	0.214

3.6. Discussion.

The results of this study demonstrated that the application of WCB, sepiolite, and particularly the WCB/sepiolite composite significantly affected Cd uptake, accumulation, and translocation in maize plants. In general, Cd accumulation was highest in the roots, followed by leaves, stems, and lowest in the grains. Most importantly, the relatively low Cd concentrations observed in grains indicate a reduced risk of Cd entry into the food chain. The distribution of Cd among plant tissues has important implications for both plant physiology and agricultural safety. The high accumulation of Cd in roots suggests that root tissues function as the primary barrier limiting Cd transport to aboveground organs. While this mechanism helps protect grains from excessive Cd contamination, elevated Cd concentrations in roots may still affect root growth, nutrient uptake, and overall plant development under prolonged exposure. Cadmium accumulation in leaves and stems may also influence photosynthetic activity and biomass production. Most importantly, the relatively low Cd concentrations observed in grains indicate a reduced risk of Cd entry into the food chain, which is particularly important for ensuring the safety of maize used for human consumption and animal feed. Therefore, treatments that promote Cd retention in roots while minimizing grain accumulation are desirable for the sustainable management of Cd-contaminated agricultural soils. This distribution is consistent with the known uptake and transport behavior of Cd in plants, where the root system serves as the primary site of contact with contaminated soil and acts as the first physiological barrier, retaining a substantial proportion of Cd to restrict its translocation to aboveground tissues [7]. The individual application of WCB or sepiolite showed a tendency to reduce Cd accumulation in different plant organs; however, the effectiveness was inconsistent among maize varieties and plant tissues. This effect is mainly associated with the Cd adsorption capacity of the materials and their influence on soil physicochemical properties. According to Bashir et al. (2020) and Duan et al. (2023), the mechanisms responsible for Cd²⁺ immobilization by biochar and sepiolite include ion exchange, electrostatic adsorption, precipitation, and complexation with surface functional groups [8, 12]. Biochar, with its highly porous structure, large surface area, and abundant oxygen-containing functional groups, can adsorb Cd through surface

interactions and ion exchange, while also increasing soil pH, thereby promoting the precipitation of Cd into less soluble forms [23, 24]. In contrast, sepiolite, with its fibrous porous structure and strong cation exchange capacity, can immobilize Cd through both physical and chemical adsorption [25]. However, when applied individually, especially under conditions of relatively high Cd contamination, the remediation efficiency remained limited. In contrast, the combined WCB/sepiolite treatments, particularly W2S2 and W2S1, exhibited significantly greater reductions in Cd accumulation across most plant organs, especially roots, stems, and grains, suggesting the presence of a synergistic effect between the two materials. The combination of WCB and sepiolite may increase the total number of adsorption sites, enhance porosity, and increase the density of oxygen-containing functional groups on the material surface, thereby improving Cd²⁺ binding capacity. The immobilization mechanisms of the composite material may involve: (i) electrostatic adsorption within pore systems and on material surfaces; (ii) ion exchange between Cd²⁺ and pre-existing cations on the surface; (iii) precipitation of Cd into poorly soluble compounds; and (iv) complexation between Cd and oxygen-containing functional groups such as –OH, –COOH, and –C=O [16, 26]. Qin et al. (2019) similarly reported that the combination of biochar and sepiolite enhanced Cd immobilization efficiency compared with the individual materials, while Zeng et al. (2025) observed a significant reduction in Cd accumulation in maize following the application of this combined amendment [16, 17].

Beyond direct adsorption, the effectiveness of the composite material may also be associated with changes in soil physicochemical properties. Biochar and sepiolite can increase soil pH through ion exchange and the release of alkaline mineral components, thereby reducing Cd mobility in soil [12, 27]. As soil pH increases, Cd tends to transform into less soluble and less bioavailable forms, resulting in lower concentrations of available Cd in the soil solution [2]. In addition, biochar may increase the concentration of dissolved organic carbon (DOC) and soil organic carbon, which can further immobilize Cd through complexation with organic matter and reduce its bioavailability [28]. These changes may explain why the combined treatments showed more stable and effective performance compared with the individual application of each material. The differences in treatment effectiveness among the three maize varieties indicate that genetic factors play an important role in Cd uptake and translocation. LVN10 tended to accumulate higher Cd concentrations in certain plant organs, particularly roots and grains, suggesting a strong capacity for Cd retention in root tissues while still maintaining relatively high translocation to reproductive organs. In contrast, NK7328 and CP511 exhibited better control over Cd accumulation under certain treatment conditions, especially when the composite amendments were applied. These differences may be associated with variations in root morphology, expression of metal ion transporter proteins, vacuolar sequestration capacity, and phytochelatin synthesis among the varieties. The BCF results showed that the treatments, particularly W2S2 and W2S1, significantly reduced Cd accumulation from soil to grain, highlighting their practical significance for food safety. Meanwhile, all TF values remained below 1, indicating that Cd was not readily translocated from vegetative tissues to the grains. This reflects the plant's inherent protective mechanism to restrict heavy metal accumulation in reproductive organs. However, TF did not always decrease proportionally with BCF, suggesting that Cd translocation within the plant is influenced not only by soil amendment treatments but also by the intrinsic physiological characteristics of each maize variety.

Although the results demonstrate the clear potential of the WCB/sepiolite composite material in reducing Cd accumulation in maize, several limitations should be acknowledged. The experiment was conducted under artificially Cd-contaminated soil conditions with a relatively short evaluation period; therefore, the findings may not fully reflect long-term variations under actual agricultural field conditions. In addition, the study did not directly analyze changes in the chemical speciation of Cd in soil following treatment, meaning that the proposed immobilization mechanisms were inferred primarily from experimental observations and previous studies. Therefore, further long-term investigations incorporating Cd speciation analysis, soil property assessments, and crop yield evaluation are needed to better elucidate the underlying mechanisms and practical applicability of this remediation approach. Beyond its effectiveness in reducing Cd accumulation, the W2S2 treatment may offer practical benefits for agricultural production. By decreasing Cd transfer to maize grains, this treatment could improve crop safety and reduce potential risks to human health. In addition, biochar and sepiolite may contribute to long-term improvements in soil quality through enhanced nutrient retention, increased cation exchange capacity, and improved soil structure. From a practical perspective, both materials are relatively inexpensive and readily available, making large-scale application feasible in Cd-contaminated agricultural areas. However, long-term field studies are still required to evaluate the persistence of Cd immobilization, effects on crop productivity, and economic feasibility under real farming conditions. Overall, the findings indicate that the composite material derived from WCB and sepiolite, particularly the W2S2 treatment, represents a promising strategy for Cd immobilization in contaminated soils. Its application can effectively reduce Cd uptake, accumulation, and translocation in maize, thereby improving crop safety and supporting the sustainable management of heavy metal-contaminated agricultural land.

4. Conclusions

This study demonstrated that the wood chip biochar–sepiolite (WCB/ sepiolite) composite effectively reduced Cd uptake, accumulation, and translocation in maize grown on Cd-contaminated soil. Among the tested treatments, W2S2 (0.2% WCB + 0.6% sepiolite) showed the highest effectiveness, significantly decreasing Cd concentrations in roots, stems, leaves, and grains, while reducing bioconcentration factors and maintaining low translocation factors. These findings indicate that the WCB/sepiolite composite is a promising and environmentally friendly amendment for mitigating Cd risks and improving the safety of maize production in contaminated agricultural soils. However, this study was conducted under artificially contaminated conditions and over a relatively short experimental period. Therefore, the long-term stability of Cd immobilization and its effects on soil properties, crop productivity, and environmental sustainability require further investigation. Future studies should evaluate the performance of the WCB/sepiolite composite under long-term field-scale conditions across different soil types, climatic regions, and cropping systems to support its practical application in sustainable agricultural management.

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Author Contribution

Trinh Tu Anh: Conceptualization, Methodology, Writing; Nguyen Thi Xuyen: Methodology, Data Analysis, Writing; Le Thi Hien and Do Dat: Data Collection, Data Analysis.

Competing Interest

The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this paper.

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