

## Health & Ecological Risk Assessment

# Agricultural byproduct-derived biochar for mitigating trace metal risks from soil to rice to public health: implications for sustainable management

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### Abstract

Heavy metal contamination in soil and its accumulation in rice poses a health risk to over 50% of the global population. Simultaneously, the poor management and underutilization of agricultural biomass waste presents an additional environmental challenge. Converting this biomass into biochar offers a potential solution to these challenges. This study evaluated biochar impacts on soil trace element content, rice plant uptake, translocation, accumulation, and associated human health risks while identifying rice response mechanisms to biochar application. A two-season field experiment was conducted using five treatments: T1 (no biochar), T2 and T3 (10 and 20 tons of rice-husk biochar), and T4 and T5 (10 and 20 tons of longan biochar). Eight trace elements, categorized as micronutrients (Fe, Mn, Cu, Zn) and toxic elements (Cd, Pb, Co, Ni), were measured in rice roots, stems, grains, and soil. Biochar application reduced the heavy metal pollution index (HPI) by 5.9% to 11.4% for micronutrients and 2.8% to 4.4% for toxic elements compared with T1. Translocation, bioaccumulation, and phytoextraction indexes tended to increase with biochar, and the hazard index decreased by 5.1%–9.5% for micronutrients and 1.3%–8.5% for toxic elements, indicating reduced health risks. These results highlight biochar's dual role in enhancing trace element phytoextraction and reducing health risks, with a more pronounced effect on micronutrients. Rice plants responded to reduced micronutrient availability by boosting uptake while lowering toxic element absorption when HPI was high. Transforming agricultural waste into biochar for rice cultivation offers multiple benefits, promoting agricultural sustainability, environmental health, and consumer safety.

**Keywords:** bioaccumulation, heavy metal pollution index, human health risks, phytoextraction potential, translocation

### Introduction

Rice (*Oryza sativa* L.) serves as the primary food source for over half of the global population, particularly in Asia, Latin America, and parts of Africa (Mali et al., 2023). As such, the presence of trace elements (TEs) in rice poses serious health risks to a substantial portion of the global population. Trace elements can bioaccumulate in living organisms, posing significant health threats, including mortality, through the food chain (Jamil Emon et al., 2023; Mitra et al., 2022). Given that rice plants inevitably absorb TEs, minimizing TE levels in rice is crucial, especially in regions with heavy metal contamination, to ensure food safety. Although global agricultural production generates vast amounts of biomass byproducts, their improper management remains a significant challenge (Kumar et al., 2023). Converting this biomass into biochar for rice cultivation could address these issues. Research has extensively explored biochar's ability to reduce greenhouse gas emissions, improve soil quality, and boost rice growth and yield (Bagheri Novair et al., 2023; Joseph et al., 2021). Despite advancements in understanding biochar's role in soil remediation, research on its effects on rice plants, including trace metal translocation, bioaccumulation, phytoextraction, and

human health implications, remains insufficient. Comprehensive studies are needed to elucidate the complex interactions between biochar, soil, rice, and human health.

Trace elements are minerals present at low concentrations in the environment and living organisms, essential for biological functions at trace levels but toxic at higher concentrations (Farooq et al., 2016; Hossain et al., 2021). Classifications of TEs vary across studies (Hossain et al., 2021; Shaik & Pachava, 2017). Based on their roles in plants, TEs can be categorized into micronutrients and toxic elements. Micronutrients, including iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn), are crucial for rice growth but can become detrimental at elevated levels (Ahmed et al., 2024; Das, 2014; Elango et al., 2022). Conversely, toxic elements such as cadmium (Cd), lead (Pb), nickel (Ni), and cobalt (Co), pose significant health risks to both plants and humans (Uddin et al., 2021; Yadav, 2010). Studies show that biochar application can significantly reduce TE bioavailability in soils, though the effects vary by element (Barčauskaitė et al., 2023; Guo, 2020a; Huang et al., 2024; Namgay et al., 2010). For example, two micronutrients, Zn and Cu, were less immobilized compared with Ni, Cr, and Pb (Barčauskaitė et al., 2023). These changes in TE

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analysis. These plant samples were thoroughly washed with tap water and then triple-rinsed with distilled water. Roots and straw were cut into small pieces, and all plant materials were oven-dried at 75 °C for 24 hr (Luo et al., 2024). Rice husks were separated from the grains, and all dried plant samples were ground into powder. The powdered samples were stored in plastic bags until analysis (Aziz et al., 2023). Soil samples were also collected from the 0–15 cm layer of each plot using a stainless-steel auger. These samples were transferred to the laboratory, air-dried, sieved through a 2-mm mesh, and stored for subsequent TE analysis.

Eight TEs (Fe, Mn, Cu, Zn, Cd, Pb, Co, and Ni) were analyzed in rice biomass and soil samples using inductively coupled plasma-optical emission spectrometry (Nguyen et al., 2022) following sample digestion or extraction. Plant samples (roots, stems, and grains) underwent wet digestion (Guadie et al., 2022), whereas soil samples required a different extraction procedure. Approximately 0.3 g of each rice powder sample was accurately weighed into clean 100 ml borosilicate flasks. A concentrated acid mixture consisting of 3 ml nitric acid (69%–72%), 2 ml perchloric acid (70%), and 1 ml hydrogen peroxide (30%) was added to each sample (Guadie et al., 2022). The samples were digested at 200 °C for 2.5 hr using a Kjeldahl apparatus until clear and colorless solutions were obtained. After cooling, the digested solutions were filtered through Whatman No. 42 filter paper and diluted to 50 ml with deionized water in volumetric flasks. A blank sample was subjected to the same digestion procedure. Approximately 0.5 g of air-dried soil was accurately weighed into a 50 ml centrifuge tube. Thirty milliliters of 0.1 M barium chloride solution was added to each tube, followed by shaking for 2 hr (Carter & Gregorich, 2008). The resulting suspensions were filtered through Whatman No. 42 filter paper. All prepared extracts were stored at 4 °C until further analysis.

Quality control and assurance for determining eight TEs in rice and soil-extracted solutions were conducted following the principles outlined by Zhao et al. (2023b). The process involved four key steps: (1) maintaining the cleanliness of the tubing system and analytical instruments before and after analysis to minimize contamination, (2) using high-purity argon gas with an appropriate ventilation system exhaust volume, (3) establishing a standard curve (coefficient of determination > 0.98) using eight calibration solutions with known metal concentrations, and (4) reanalyzing two calibration standard solutions with predetermined TE concentrations after every 15 samples to ensure accuracy and stability during analysis. Additionally, recovery tests were performed by spiking known concentrations of analytical standards into sample solutions extracted from soil, rice-husk biochar, and longan biochar. Sample spikes were prepared by adding standard solutions to samples at three concentration levels (50%, 100%, and 150% of expected analyte concentrations). The spiked samples were processed through the entire analytical procedure. The average recoveries for the eight trace elements ranged from 91.9%–108.4% ( $n=3$  for each concentration level). Although standard reference materials or certified reference materials were not used in this study due to some reasons, additional measures, including calibration standards (eight calibration solutions with predetermined concentrations were used to establish standard curves with a coefficient of determination > 0.98), routine recalibration (calibration standards were reanalyzed after every 15 samples to check for instrument drift and ensure consistency), spiked recovery tests, and instrument maintenance (the cleanliness of analytical instruments and tubing systems was strictly maintained before and after analysis to

minimize contamination) were implemented to validate the analytical process, confirming the accuracy and reliability of the quantification.

## Calculations

Heavy metal pollution index (HPI), translocation index (TI), bioaccumulation index (BI), and phytoextraction potential index (PI) were measured and detailed procedures as well as explanations for each index are shown in [online supplementary material Text 1](#). The HPI was calculated using [Equation 1](#) (Prasad Ahirvar et al., 2023; Ugungwa & Kgabi, 2021):

$$\text{HPI} = \frac{\sum_{i=1}^n Q_i W_i}{\sum_{i=1}^n W_i} \quad (\text{Eq. 1})$$

where  $n$  is the number of TEs examined;  $W_i$  is equal to  $\frac{1}{S_i}$ ;  $S_i$  is the maximum permissible limit for the  $i^{\text{th}}$  TE in soil (see [online supplementary material Table 2](#)); and  $Q_i = \frac{V_i}{S_i} \times 100$ ;  $V_i$  is the measured concentration of the  $i^{\text{th}}$  element. The HPI was calculated separately for the micronutrient group (MN-HPI: Fe, Mn, Cu, Zn) and the toxic-element group (TX-HPI: Cd, Pb, Co, Ni) to allow for comparison. An HPI value below 100 indicates a low risk of TE pollution in soil, whereas values of 100 or above suggest a high risk.

The translocation factor (TF) was calculated using [Equation 2](#):

$$\text{TF} = \frac{C_{\text{shoot}}}{C_{\text{root}}} \quad (\text{Eq. 2})$$

where  $C_{\text{shoot}}$  and  $C_{\text{root}}$  are the concentration of a TE in the shoot and root, respectively. All TF values below 1 indicate root retention, whereas values above 1 suggest efficient translocation (Aziz et al., 2023).

The TI was computed based on [Equation 3](#):

$$\text{TI} = \sqrt[n]{\text{TF}_1 \times \text{TF}_2 \dots \text{TF}_n} \quad (\text{Eq. 3})$$

where  $n$  is the number of TEs and  $\text{TF}_1 \times \text{TF}_2 \dots \text{TF}_n$  are the TF of individual TEs. The TI was computed for the micronutrient group (MN-TI; Fe, Mn, Cu, Zn) and toxic-element group (TX-TI; Cd, Pb, Co, and Ni) for comparison.

The bioaccumulation factor (BF) was calculated using [Equation 4](#):

$$\text{BF} = \frac{C_p}{C_s} \quad (\text{Eq. 4})$$

where  $C_p$  is the concentration of TEs in the rice part, and  $C_s$  is the concentration of TEs in the soil. A BF level exceeding 1.00 indicates a rice's ability to accumulate metals, whereas a BF below 1.00 suggests rice's absorption of trace metal (Aziz et al., 2023).

The BI was calculated using [Equation 5](#):

$$\text{BI} = \sqrt[n]{\text{BF}_1 \times \text{BF}_2 \dots \text{BF}_n} \quad (\text{Eq. 5})$$

The BI was computed for the micronutrient group (MN-BF) and the toxic-element group (TX-BF).

The phytoextraction potential factor (PF) was calculated using [Equation 6](#)

$$\text{PF} = C_i \times \text{Rice biomass} \quad (\text{Eq. 6})$$

where  $C_i$  is the concentration of a TE and *Rice biomass* is the aboveground biomass of rice per ha.

The PI was computed using Equation 7:

$$PI = \sqrt[n]{PF_1 \times PF_2 \dots PF_n} \quad (\text{Eq. 7})$$

The PI was also computed for the micronutrient group (MN-PI) and toxic-element group (TX-PI).

### Human health risk assessment

Human health risk assessment involves three steps calculating the estimated daily intake (EDI), determining the hazard quotient (HQ), and evaluating the hazard index (HI). The EDI is computed using Equation 8, which serves as the foundation for assessing the potential health risks associated with TE exposure (Guo et al., 2020a):

$$EDI = \frac{DCR \times C}{BW} \quad (\text{Eq. 8})$$

The daily rice consumption rate for adults was assumed to be 0.2383 kg per person, and the average adult body weight (BW) was set at 60.6 kg (Guo et al., 2020a). Metal concentration in the rice grain was denoted as C. The HQ was computed using Equation 9:

$$HQ = \frac{EDI}{R_{fd}} \quad (\text{Eq. 9})$$

where  $R_{fd}$  is reference dose, shown in online supplementary material Table 2. The  $R_{fd}$  is established by the U.S. Environmental Protection Agency (USEPA) as estimates of the daily oral exposure to a chemical that is likely to be without an appreciable risk of adverse noncancer health effects over a lifetime (USEPA, 1989). The HI was computed using Equation 10:

$$HI = \sum HQ \quad (\text{Eq. 10})$$

The HI was calculated separately for the micronutrient group (MN-HI) and the toxic-element group (TX-HI) for comparison. An HI value below 1 suggests a low risk of adverse health effects, values above 1 indicate a potential risk, and values exceeding 10 represent a substantial risk (Zhao et al., 2023a).

We additionally calculated the reduction efficiency of HPI (RE-HPI) by biochar using Equation 11 for both micronutrient and toxic-element nutrient groups.

$$RE - HPI = \frac{HPI_{T1} - HPI_{biochar \text{ treatment}}}{HPI_{T1}} * 100 \quad (\text{Eq. 11})$$

where  $HPI_{T1}$  and  $HPI_{biochar \text{ treatment}}$  are heavy pollution index for treatment 1 and biochar treatments, respectively.

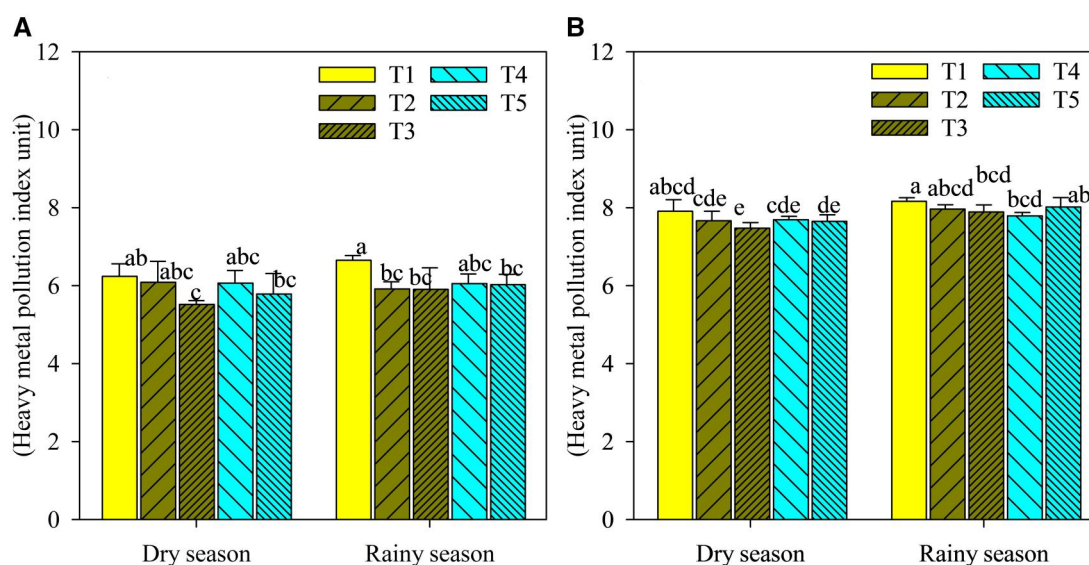
### Statistical analyses

The experiment was conducted using a randomized complete block design with three replications. Statistical analyses were performed using JMP Pro 18 software (SAS Institute Inc., Cary, NC, USA). A two-way ANOVA was used to evaluate the effects of growing season and biochar application rates, as well as their interactions, on all measured parameters and calculated indices. Prior to analysis, data were tested for normality and homogeneity of variance. Relationships between various indices were examined using Pearson's correlation analysis. Statistical significance was set at  $p < .05$  for all analyses.

## Results

### Trace element status in tested soil

Biochar application reduced exchangeable TEs in soil compared with the control (see online supplementary material Figure 1). Treatment 3 (20 tons rice-husk biochar) resulted in the lowest concentrations of exchangeable Fe, Cu, Zn, and Cd whereas the control had the highest levels of exchangeable Fe, Mn, Cu, Cd, and Pb. The HPI was calculated from these concentrations and shown in Figure 1. Treatment 3 showed significantly lower HPI values for both micronutrient and toxic element groups across seasons, and the control had the highest. The HPI for the micronutrient group in T3 was 5.52 during the dry season and 5.92 during the rainy season. For the toxic element group, the HPI in T3 was 7.47 in the dry season and 7.89 in the rainy season. On average, the HPI for the micronutrient group (6.03) was significantly lower than that of the toxic element group (7.82), as confirmed by an additional t-test analysis.



**Figure 1.** Heavy metal pollution index (HPI) of the micronutrients (A) and toxic elements (B) in five treatments and two seasons. Within a panel, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ . Error bars indicate the SD of the means.

## Translocation, bioaccumulation, and phytoextraction of TEs in rice

Trace element levels in rice parts varied across elements, treatments, and seasons, with biochar generally reducing levels compared with the control (see [online supplementary material Figures 2–4](#)). Translocation factors differed among elements and treatments ([Table 1](#)). The MN-TI was lowest in T1 (0.76) and highest in T3 (0.88) during the dry season ([Figure 2](#)). The TX-TI was similar across treatments ranging from 0.55–0.67 in both seasons. A t-test revealed that the average MN-TI (0.81) was significantly higher than the TX-TI (0.60), indicating that rice plants translocate micronutrients from root to shoot more efficiently than toxic elements.

[Table 2](#) shows the BF for eight TEs with significant differences in BFs found across the five treatments in both seasons. For micronutrients, the highest BF values were for Fe in T5 (18.45) and Mn in T3 (2.58) during the dry season, Cu in T4 and T5 (0.24) during the rainy season, and Zn in T3 (58.16) during the rainy season. For toxic elements, T1 had the highest BF for Cd (1.21) and Co (0.47) during the dry season, whereas T2 had the highest for Pb (2.15) and T4 for Ni (8.12) in the dry season. Biochar application generally increased MN-BI values compared with the no-biochar treatment, particularly during the dry season ([Figure 3](#)). The highest MN-BI values were in T5 during the dry season (3.58) and T3 during the rainy season (4.44). In contrast, T4 had the highest TX-BI values in both the dry (1.75) and rainy (1.45) seasons. A t-test confirmed that average MN-BI values (3.57) were significantly higher than TX-BI values (1.54).

Treatments 2 and 3 (rice-husk biochar at 10 and 20 tons/ha) showed the highest PFs for most metals across seasons ([Table 3](#)). In the dry season, T3 recorded the highest PF values for Mn (1.23 kg ha<sup>-1</sup>), Cd (0.0043 kg ha<sup>-1</sup>), Co (0.21 kg ha<sup>-1</sup>), and Ni (0.08 kg ha<sup>-1</sup>), whereas T1 had the lowest PF values for many elements during the rainy season. Treatment 3 had the highest PI values for both groups in the dry season, with 0.49 for micronutrients and 0.033 for toxic elements ([Figure 4](#)). In contrast, T1 had the lowest PI values across both seasons and element groups.

A t-test revealed that the average PI for micronutrients (0.41) was significantly higher than for toxic elements (0.025).

## Human risk of heavy metals in rice grain

In the dry season, T1 exhibited the highest EDI values for Fe (1.22 mg kg<sup>-1</sup> day<sup>-1</sup>), Cd (0.00085 mg kg<sup>-1</sup> day<sup>-1</sup>), Pb (0.0056 mg kg<sup>-1</sup> day<sup>-1</sup>), Co (0.047 mg kg<sup>-1</sup> day<sup>-1</sup>), and Ni (0.0189 mg kg<sup>-1</sup> day<sup>-1</sup>; see [online supplementary material Table 3](#)). Treatment 1 also had the highest EDI for Cu in the rainy season (0.008 mg kg<sup>-1</sup> day<sup>-1</sup>), whereas Zn peaked in T5 during the dry season (0.05 mg kg<sup>-1</sup> day<sup>-1</sup>). The corresponding HQ values were also highest in T1 during the dry season for Fe (12.2), Cd (0.85), Pb (1.60), Co (0.11), and Ni (0.95; [Table 4](#)). In contrast, T3 in the dry season had the lowest HQ values for Cu, Zn, and Co, and during the rainy season for Fe, Mn, Cd, and Pb. These results suggest that T1 (no biochar) consistently had higher EDI and HQ values, indicating increased health risks, whereas T3 (20 tons/ha rice-husk biochar) had the lowest values, demonstrating its effectiveness in reducing heavy metal uptake and associated health risks.

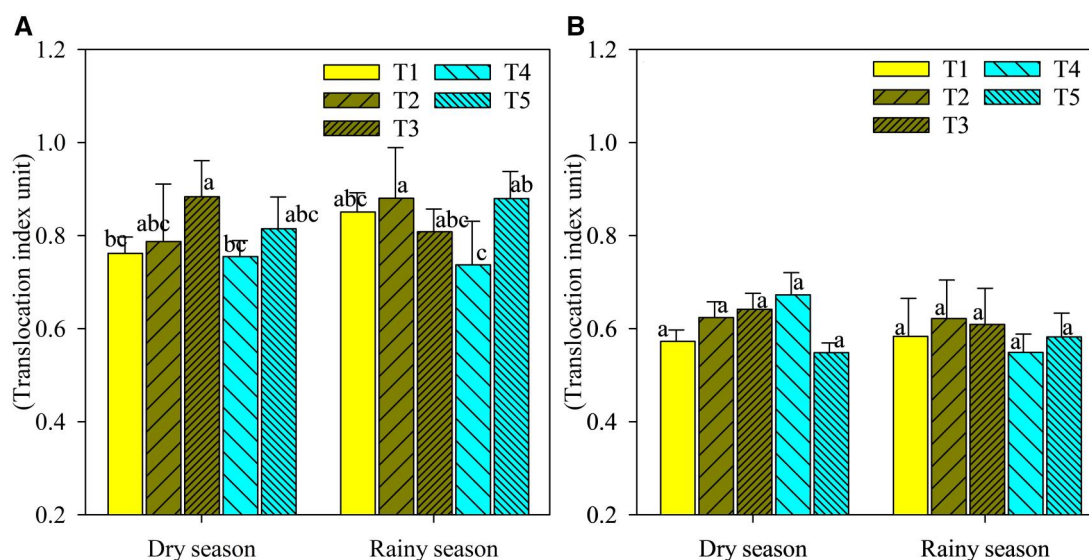
The HI for all eight examined metals, shown in [Figure 5](#), reveals that T1 consistently had the highest HI values across both metal groups and seasons, whereas T3 had the lowest. For micronutrients, the highest HI in the dry season was in T1 (12.65), followed by T5, T4, T2, and T3 (11.03). Treatment 1 also recorded the highest TX-HI at 3.50, with T3 having the lowest at 2.98. In the rainy season, HI values were similar across all treatments for both metal groups. On average, the HI for micronutrients (11.05) was significantly higher than that for toxic elements (2.90), as confirmed by a t-test.

Among the four calculated indices—TI, BI, PI, and HI—the BI and HI for the toxic elements showed statistically significant correlations with the HPI ([Figure 6](#)). The relationships between TX-BI and HPI, as well as TX-HI and HPI, were both inversely correlated, with the TX-BI correlation having a coefficient of determination of 0.28. No significant correlations were found between HPI and the four indices for micronutrients. These findings suggest rice plants respond differently to

**Table 1.** Translocation factor of eight heavy metals in rice of five treatments in two seasons.

Rice season	Treatment	Micronutrient group				Toxic element group			
		Fe	Mn	Cu	Zn	Cd	Pb	Co	Ni
Dry season	T1	0.07 <sup>b</sup> (0.01)	1.83 <sup>b,c</sup> (0.18)	1.45 <sup>a</sup> (0.17)	1.85 <sup>a</sup> (0.57)	0.47 <sup>a,b</sup> (0.09)	0.44 <sup>a,b</sup> (0.16)	0.42 <sup>c,d</sup> (0.01)	1.32 <sup>a</sup> (0.14)
	T2	0.07 <sup>b</sup> (0.02)	1.78 <sup>b,c</sup> (0.16)	1.61 <sup>a</sup> (0.13)	1.86 <sup>a</sup> (0.68)	0.56 <sup>a,b</sup> (0.05)	0.38 <sup>a,b,c</sup> (0.03)	0.40 <sup>c,d</sup> (0.02)	1.81 <sup>a</sup> (0.36)
	T3	0.13 <sup>a</sup> (0.02)	1.75 <sup>c</sup> (0.23)	1.57 <sup>a</sup> (0.2)	1.70 <sup>a</sup> (0.3)	0.61 <sup>a,b</sup> (0.06)	0.35 <sup>a,b,c</sup> (0.07)	0.41 <sup>c,d</sup> (0.02)	1.96 <sup>a</sup> (0.47)
	T4	0.08 <sup>b</sup> (0.03)	1.77 <sup>c</sup> (0.3)	1.51 <sup>a</sup> (0.11)	1.63 <sup>a</sup> (0.43)	0.62 <sup>a</sup> (0.09)	0.45 <sup>a</sup> (0.11)	0.40 <sup>d</sup> (0.01)	1.95 <sup>a</sup> (0.53)
	T5	0.09 <sup>a,b</sup> (0.01)	1.72 <sup>c</sup> (0.11)	1.61 <sup>a</sup> (0.07)	1.68 <sup>a</sup> (0.21)	0.58 <sup>a,b</sup> (0.1)	0.27 <sup>c</sup> (0.06)	0.43 <sup>b,c,d</sup> (0.02)	1.46 <sup>a</sup> (0.33)
Rainy season	T1	0.09 <sup>b</sup> (0.01)	2.26 <sup>a,b</sup> (0.19)	1.40 <sup>a</sup> (0.41)	1.97 <sup>a</sup> (0.4)	0.46 <sup>a,b</sup> (0.15)	0.32 <sup>a,b,c</sup> (0.16)	0.47 <sup>a,b</sup> (0.04)	1.93 <sup>a</sup> (0.19)
	T2	0.09 <sup>a,b</sup> (0.02)	2.52 <sup>a</sup> (0.59)	1.53 <sup>a</sup> (0.32)	1.71 <sup>a</sup> (0.19)	0.57 <sup>a,b</sup> (0.03)	0.29 <sup>a,b,c</sup> (0.12)	0.48 <sup>a</sup> (0.05)	2.00 <sup>a</sup> (0.37)
	T3	0.08 <sup>b</sup> (0.01)	2.12 <sup>a,b,c</sup> (0.06)	1.46 <sup>a</sup> (0.3)	1.81 <sup>a</sup> (0.3)	0.45 <sup>b</sup> (0.13)	0.28 <sup>b,c</sup> (0.08)	0.49 <sup>a</sup> (0.03)	2.31 <sup>a</sup> (0.34)
	T4	0.07 <sup>b</sup> (0.01)	2.06 <sup>a,b,c</sup> (0.09)	1.10 <sup>a</sup> (0.23)	1.77 <sup>a</sup> (0.4)	0.49 <sup>a,b</sup> (0.08)	0.29 <sup>a,b,c</sup> (0.01)	0.45 <sup>a,b,c</sup> (0.04)	1.51 <sup>a</sup> (0.64)
	T5	0.09 <sup>a,b</sup> (0.01)	2.38 <sup>a</sup> (0.46)	1.62 <sup>a</sup> (0.31)	1.82 <sup>a</sup> (0.55)	0.46 <sup>a,b</sup> (0.1)	0.28 <sup>b,c</sup> (0.03)	0.47 <sup>a,b</sup> (0.01)	1.93 <sup>a</sup> (0.14)

Note. The numbers in parentheses are the SD of the means. Within a column, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ .



**Figure 2.** Translocation index (TI) of the micronutrients (A) and toxic elements (B) in five treatments and two seasons. Within a panel, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ . Error bars indicate the SD of the means.

**Table 2.** Bioaccumulation factor of eight heavy metals in rice of five treatments in two seasons.

Rice season	Treatment	Micronutrient group				Toxic element group			
		Fe	Mn	Cu	Zn	Cd	Pb	Co	Ni
Dry season	T1	16.88 <sup>a,b</sup> (2.28)	2.33 <sup>a,b,c</sup> (0.15)	0.21 <sup>a,b,c</sup> (0.01)	11.08 <sup>e</sup> (1.87)	1.21 <sup>a</sup> (0.12)	2.01 <sup>a,b</sup> (0.02)	0.47 <sup>a</sup> (0.03)	7.57 <sup>a,b</sup> (1.63)
	T2	15.60 <sup>b,c</sup> (2.24)	2.51 <sup>a,b</sup> (0.07)	0.18 <sup>c,d</sup> (0.01)	13.67 <sup>de</sup> (0.94)	1.19 <sup>a,b</sup> (0.08)	2.15 <sup>a</sup> (0.15)	0.46 <sup>a,b</sup> (0.04)	6.45 <sup>a,b,c</sup> (0.11)
	T3	16.57 <sup>a,b,c</sup> (1.76)	2.58 <sup>a</sup> (0.16)	0.19 <sup>b,c,d</sup> (0.01)	17.61 <sup>c,d</sup> (1.87)	1.11 <sup>a,b,c,d</sup> (0.05)	2.06 <sup>a,b</sup> (0.27)	0.43 <sup>b,c</sup> (0.01)	6.17 <sup>b,c</sup> (1.18)
	T4	16.10 <sup>a,b,c</sup> (1.85)	2.51 <sup>a,b</sup> (0.13)	0.21 <sup>a,b,c</sup> (0.01)	15.34 <sup>c,d,e</sup> (1.2)	1.17 <sup>a,b,c</sup> (0.11)	2.13 <sup>a</sup> (0.35)	0.47 <sup>a,b</sup> (0.02)	8.12 <sup>a</sup> (1.87)
	T5	18.45 <sup>a</sup> (1.98)	2.55 <sup>a,b</sup> (0.03)	0.18 <sup>d</sup> (0.01)	19.70 <sup>c</sup> (2.43)	1.21 <sup>a</sup> (0.12)	1.96 <sup>a,b</sup> (0.13)	0.45 <sup>a,b</sup> (0.01)	7.41 <sup>a,b</sup> (1.36)
Rainy season	T1	13.92 <sup>c</sup> (0.67)	2.46 <sup>a,b</sup> (0.33)	0.23 <sup>a,b</sup> (0)	20.52 <sup>c</sup> (0.76)	1.01 <sup>d</sup> (0.03)	1.45 <sup>c</sup> (0.15)	0.43 <sup>a,b,c</sup> (0.01)	5.63 <sup>c</sup> (0.45)
	T2	15.04 <sup>b,c</sup> (0.88)	2.25 <sup>b,c</sup> (0.19)	0.22 <sup>a,b</sup> (0.05)	46.75 <sup>b</sup> (3.81)	1.05 <sup>c,d</sup> (0.01)	1.71 <sup>b,c</sup> (0.35)	0.44 <sup>a,b,c</sup> (0.02)	5.49 <sup>c</sup> (0.1)
	T3	14.12 <sup>c</sup> (0.95)	2.12 <sup>c</sup> (0.04)	0.22 <sup>a,b</sup> (0.01)	58.16 <sup>a</sup> (2.52)	1.03 <sup>d</sup> (0.01)	1.37 <sup>c</sup> (0.11)	0.41 <sup>c</sup> (0.04)	5.85 <sup>b,c</sup> (0.64)
	T4	14.62 <sup>b,c</sup> (0.18)	2.36 <sup>a,b,c</sup> (0.25)	0.24 <sup>a</sup> (0.01)	18.90 <sup>c,d</sup> (0.99)	1.05 <sup>c,d</sup> (0.03)	1.53 <sup>c</sup> (0.3)	0.46 <sup>a,b</sup> (0.01)	6.08 <sup>b,c</sup> (0.44)
	T5	14.04 <sup>c</sup> (1.24)	2.33 <sup>a,b,c</sup> (0.17)	0.24 <sup>a</sup> (0.02)	15.30 <sup>c,d,e</sup> (0.86)	1.06 <sup>b,c,d</sup> (0.08)	1.51 <sup>c</sup> (0.22)	0.44 <sup>a,b,c</sup> (0.02)	6.13 <sup>b,c</sup> (0.23)

Note. The numbers in parentheses are the SD of the means. Within a column, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ .

micronutrients and toxic elements, reflecting distinct uptake and accumulation mechanisms under biochar application.

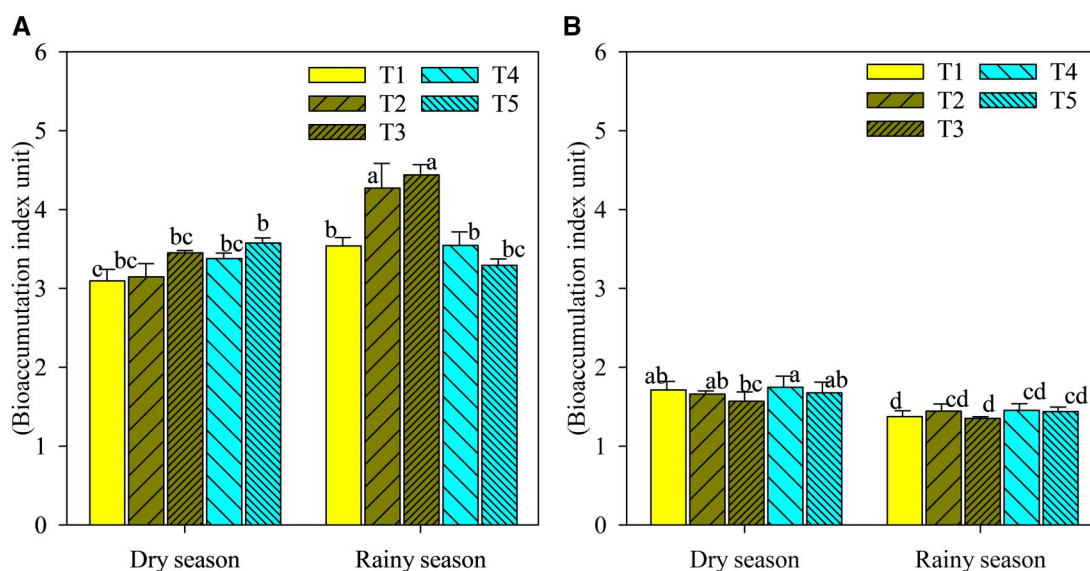
## Discussion

### Impacts of biochar on TE status in soil

The HPI is a key tool for evaluating soil quality regarding TE contamination. In this study, HPI was calculated using the concentrations of eight TEs, divided into micronutrient and toxic-element groups. Biochar-amended soils showed significantly lower HPI and element availability than soils without biochar, aligning with previous research (Ibrahim et al., 2022; Li et al., 2017; Zhu et al., 2021). Biochar reduces TE bioavailability and toxicity through mechanisms like electrostatic attraction, surface precipitation, complexation, cation exchange, and adsorption (Ghandali et al., 2024; Gu

et al., 2024; Zhang et al., 2021). These mechanisms are typically based on the high surface area, abundance of functional groups, high pH, and alkalinity in biochar, which reduces TE bioavailability by transforming them into less accessible forms (Chen et al., 2022; Wang et al., 2020; Xu et al., 2024; Zhang et al., 2021). Moreover, the reduced TE availability in biochar-amended soils can be attributed to biochar-induced pH increases, which occur through multiple mechanisms: (1) direct contribution of alkaline compounds from biochar, (2) release of basic cations during biochar decomposition, (3) proton consumption at biochar surfaces, and (4) modifications of soil redox conditions (Biswash et al., 2024; Fan et al., 2023). These pH changes play a crucial role in regulating TE mobility and availability in the soil system.

Analysis of the RE-HPI (Equation 11) revealed distinct seasonal patterns. Micronutrients showed higher reduction efficiencies,



**Figure 3.** Bioaccumulation index (BI) of the micronutrients (A) and toxic elements (B) in five treatments and two seasons. Within a panel, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ . Error bars indicate the SD of the means.

**Table 3.** Phytoextraction potential factor ( $\text{kg ha}^{-1}$ ) of eight heavy metals in rice of five treatments in two seasons.

Rice season	Treatment	Micronutrient group				Toxic element group			
		Fe	Mn	Cu	Zn	Cd	Pb	Co	Ni
Dry season	T1	3.20 <sup>a</sup> (0.25)	0.92 <sup>c</sup> (0.06)	0.05 <sup>b</sup> (0.003)	0.17 <sup>b,c,d</sup> (0.017)	0.0031 <sup>b,c</sup> (0.0003)	0.016 <sup>a,b</sup> (0.001)	0.17 <sup>b,c</sup> (0.004)	0.065 <sup>a,b,c</sup> (0.012)
	T2	3.37 <sup>a</sup> (0.49)	1.18 <sup>a,b</sup> (0.06)	0.06 <sup>a</sup> (0.003)	0.23 <sup>a</sup> (0.046)	0.0038 <sup>a,b</sup> (0.0003)	0.019 <sup>a</sup> (0.001)	0.20 <sup>a</sup> (0.009)	0.077 <sup>a</sup> (0.004)
	T3	3.95 <sup>a</sup> (0.3)	1.23 <sup>a</sup> (0.078)	0.05 <sup>a,b</sup> (0.003)	0.22 <sup>a</sup> (0.018)	0.0043 <sup>a</sup> (0.0004)	0.017 <sup>a,b</sup> (0.002)	0.21 <sup>a</sup> (0.004)	0.080 <sup>a</sup> (0.008)
	T4	3.55 <sup>a</sup> (0.54)	1.08 <sup>a,b,c</sup> (0.153)	0.05 <sup>a,b</sup> (0.004)	0.19 <sup>a,b,c</sup> (0.017)	0.0041 <sup>a</sup> (0.0003)	0.017 <sup>a,b</sup> (0.002)	0.19 <sup>a</sup> (0.025)	0.078 <sup>a</sup> (0.02)
	T5	3.42 <sup>a</sup> (0.23)	1.02 <sup>b,c</sup> (0.055)	0.05 <sup>b</sup> (0.002)	0.20 <sup>a,b</sup> (0.018)	0.0036 <sup>a,b</sup> (0.0005)	0.013 <sup>b,c</sup> (0.001)	0.18 <sup>a,b</sup> (0.011)	0.068 <sup>a,b</sup> (0.01)
Rainy season	T1	3.38 <sup>a</sup> (0.241)	1.02 <sup>b,c</sup> (0.071)	0.03 <sup>c</sup> (0.008)	0.15 <sup>d</sup> (0.005)	0.0024 <sup>c</sup> (0.0002)	0.008 <sup>d</sup> (0.003)	0.13 <sup>e</sup> (0.017)	0.044 <sup>d</sup> (0.003)
	T2	3.79 <sup>a</sup> (0.1)	1.05 <sup>a,b,c</sup> (0.05)	0.03 <sup>c</sup> (0.01)	0.15 <sup>d</sup> (0.012)	0.0030 <sup>b,c</sup> (0.0001)	0.009 <sup>dc</sup> (0.001)	0.14 <sup>de</sup> (0.014)	0.050 <sup>c,d</sup> (0.004)
	T3	3.43 <sup>a</sup> (0.86)	1.03 <sup>b,c</sup> (0.19)	0.03 <sup>c</sup> (0.002)	0.16 <sup>d</sup> (0.012)	0.0025 <sup>c</sup> (0.0001)	0.010 <sup>c,d</sup> (0.001)	0.14 <sup>c,d,e</sup> (0.02)	0.052 <sup>b,c,d</sup> (0.01)
	T4	3.43 <sup>a</sup> (0.41)	0.97 <sup>c</sup> (0.13)	0.03 <sup>c</sup> (0.01)	0.16 <sup>d</sup> (0.01)	0.0027 <sup>c</sup> (0.0003)	0.009 <sup>c,d</sup> (0.001)	0.13 <sup>de</sup> (0.011)	0.047 <sup>d</sup> (0.003)
	T5	4.02 <sup>a</sup> (0.38)	1.21 <sup>a</sup> (0.04)	0.04 <sup>c</sup> (0.004)	0.17 <sup>c,d</sup> (0.003)	0.0029 <sup>c</sup> (0.0005)	0.010 <sup>c,d</sup> (0.002)	0.15 <sup>c,d</sup> (0.014)	0.054 <sup>b,c,d</sup> (0.007)

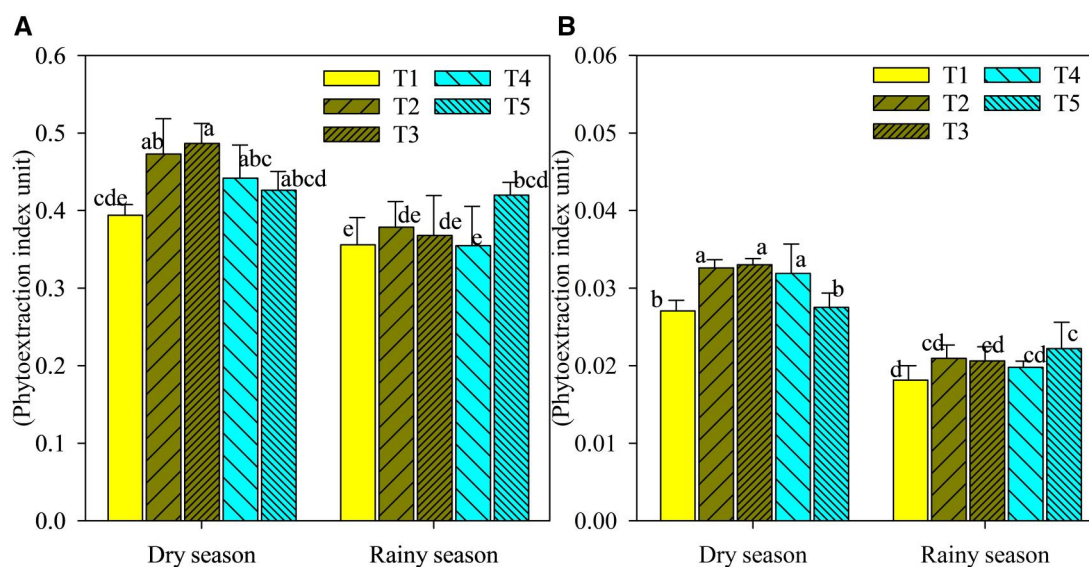
Note. The numbers in parentheses are the SD of the means. Within a column, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ .

with RE-HPI values of 6.02% and 10.18% in the dry and rainy seasons, respectively. Toxic elements demonstrated lower and more consistent reduction efficiencies across seasons, with RE-HPI values of 3.67% in the dry season and 3.03% in the rainy season. These findings support our hypothesis that biochar more effectively reduces the pollution index for micronutrients than toxic elements. This differential effect can be attributed to biochar's ability to decrease metal bioavailability in soil. This reduced bioavailability may lead to increased uptake of micronutrients by rice plants relative to toxic elements. Furthermore, the reduction of toxic elements in the soil may stimulate increased nutrient uptake, including micronutrients, through a phenomenon known as hormesis. This concept suggests that a decrease in toxic stress can improve overall plant health and nutrient acquisition efficiency (Carvalho et al., 2020; Małkowski et al., 2020). These

processes collectively contribute to a more substantial reduction in exchangeable micronutrients compared with toxic elements. Although biochar effectively mitigates TE pollution, careful management is crucial to ensure essential micronutrients remain available for optimal plant growth.

### Impacts of biochar on the processes of translocation, bioaccumulation, and phytoextraction potential of TEs in rice parts

Biochar application reduced TE concentrations in the soil, affecting their translocation, bioaccumulation, and phytoextraction in rice. Interestingly, whereas biochar decreased the exchangeable TE content in the soil, it increased the translocation, bioaccumulation, and phytoextraction of micronutrients (Figures 2–4), particularly in T2 and T3, compared with the control. However,



**Figure 4.** Phytoextraction potential index (PI) of the micronutrients (A) and toxic elements (B) in five treatments and two seasons. Within a panel, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ . Error bars indicate the SD of the means.

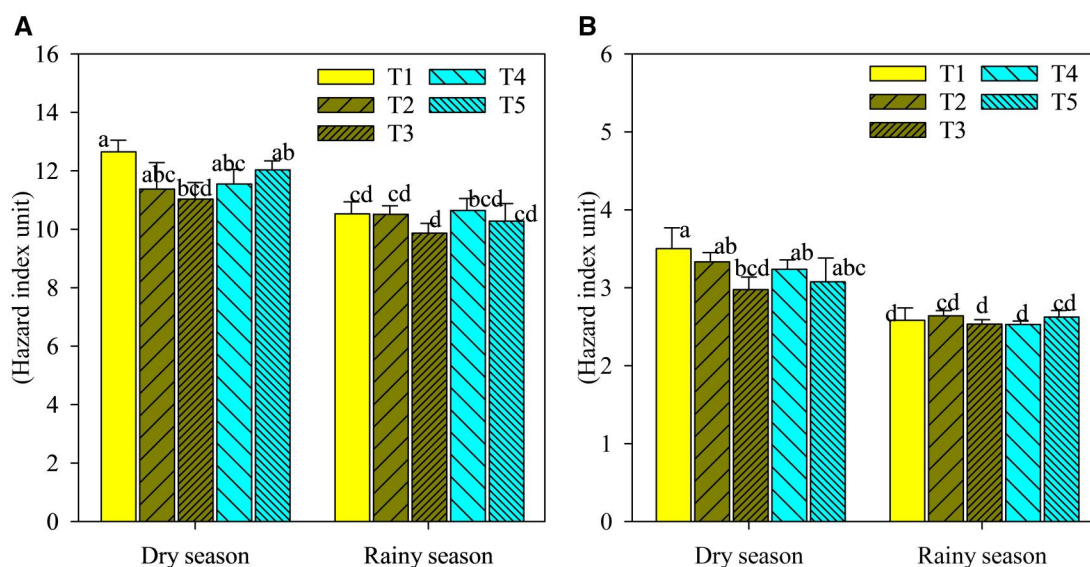
**Table 4.** Hazard quotient of heavy metals in five treatments and two seasons.

Rice season	Treatment	Micronutrient group				Toxic element group			
		Fe	Mn	Cu	Zn	Cd	Pb	Co	Ni
Dry season	T1	12.20 <sup>a</sup> (0.42)	0.14 <sup>a,b,c</sup> (0.01)	0.18 <sup>a,b,c</sup> (0.01)	0.13 <sup>c,d</sup> (0.02)	0.85 <sup>a</sup> (0.05)	1.60 <sup>a</sup> (0.02)	0.110 <sup>a</sup> (0.002)	0.95 <sup>a</sup> (0.2)
	T2	10.93 <sup>b,c,d</sup> (0.89)	0.14 <sup>a,b</sup> (0.01)	0.15 <sup>de</sup> (0.02)	0.15 <sup>a,b,c</sup> (0.03)	0.80 <sup>a,b,c</sup> (0.07)	1.62 <sup>a</sup> (0.02)	0.107 <sup>a,b</sup> (0.003)	0.81 <sup>a,b</sup> (0.03)
	T3	10.62 <sup>c,d,e</sup> (0.57)	0.14 <sup>a,b</sup> (0)	0.14 <sup>e</sup> (0.01)	0.13 <sup>d</sup> (0.01)	0.72 <sup>c,d</sup> (0.03)	1.34 <sup>a,b,c</sup> (0.07)	0.099 <sup>c</sup> (0.003)	0.82 <sup>a,b</sup> (0.13)
	T4	11.09 <sup>b,c</sup> (0.5)	0.14 <sup>a,b,c</sup> (0.01)	0.17 <sup>b,c,d</sup> (0.01)	0.15 <sup>a,b,c,d</sup> (0.01)	0.79 <sup>a,b,c</sup> (0.03)	1.40 <sup>a,b</sup> (0.22)	0.108 <sup>a</sup> (0.003)	0.94 <sup>a</sup> (0.17)
	T5	11.59 <sup>a,b</sup> (0.32)	0.14 <sup>a,b</sup> (0)	0.14 <sup>e</sup> (0.01)	0.17 <sup>a</sup> (0.02)	0.81 <sup>a,b</sup> (0.08)	1.22 <sup>b,c,d</sup> (0.11)	0.104 <sup>a,b,c</sup> (0.0003)	0.94 <sup>a</sup> (0.14)
Rainy season	T1	10.02 <sup>ef</sup> (0.43)	0.14 <sup>a</sup> (0.01)	0.20 <sup>a</sup> (0.01)	0.16 <sup>a,b</sup> (0.01)	0.72 <sup>c,d</sup> (0.02)	1.04 <sup>c,d</sup> (0.14)	0.106 <sup>a,b</sup> (0.003)	0.72 <sup>b</sup> (0.03)
	T2	10.07 <sup>ef</sup> (0.3)	0.13 <sup>c,d</sup> (0.01)	0.17 <sup>c,d</sup> (0.04)	0.15 <sup>a,b,c,d</sup> (0.01)	0.73 <sup>b,c,d</sup> (0.01)	1.09 <sup>c,d</sup> (0.08)	0.107 <sup>a,b</sup> (0.002)	0.71 <sup>b</sup> (0.05)
	T3	9.42 <sup>f</sup> (0.34)	0.12 <sup>d</sup> (0)	0.18 <sup>a,b,c</sup> (0.01)	0.14 <sup>b,c,d</sup> (0.01)	0.69 <sup>d</sup> (0.02)	1.00 <sup>d</sup> (0.06)	0.101 <sup>b,c</sup> (0.01)	0.74 <sup>b</sup> (0.05)
	T4	10.16 <sup>def</sup> (0.39)	0.13 <sup>b,c,d</sup> (0.01)	0.20 <sup>a,b</sup> (0.01)	0.15 <sup>a,b,c</sup> (0.01)	0.72 <sup>c,d</sup> (0.03)	0.99 <sup>d</sup> (0.03)	0.108 <sup>a</sup> (0.002)	0.72 <sup>b</sup> (0.02)
	T5	9.81 <sup>ef</sup> (0.61)	0.13 <sup>a,b,c,d</sup> (0)	0.19 <sup>a,b,c</sup> (0.01)	0.14 <sup>b,c,d</sup> (0.01)	0.74 <sup>b,c,d</sup> (0.08)	1.02 <sup>d</sup> (0.11)	0.107 <sup>a,b</sup> (0.001)	0.75 <sup>b</sup> (0.04)

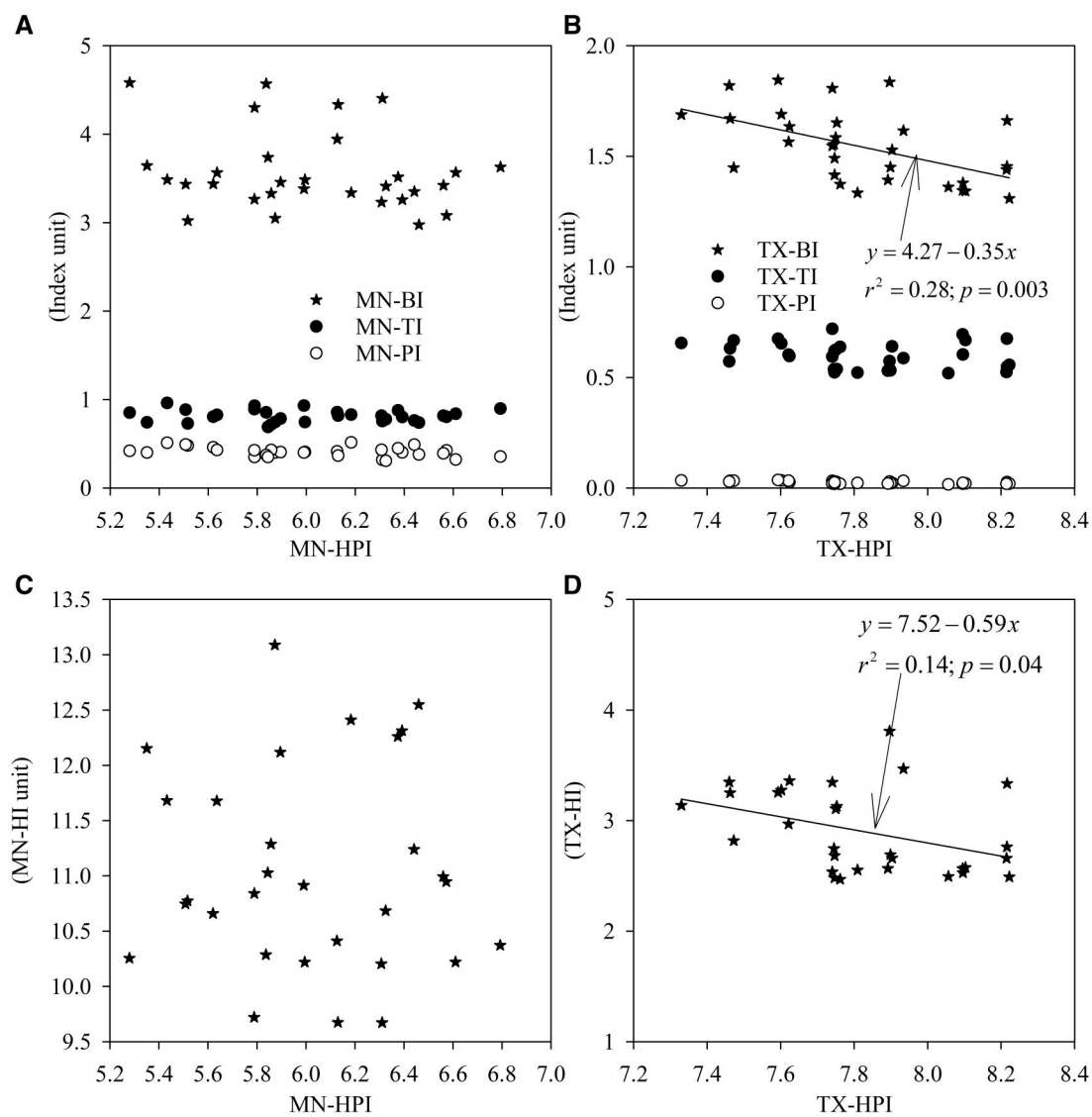
Note. The numbers in parentheses are the SD of the means. Within a column, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ .

biochar had minimal impact on these indexes for toxic elements. These findings support our second hypothesis that biochar leads to a more pronounced increase in the translocation, bioaccumulation, and phytoextraction of micronutrients relative to toxic elements. The seemingly paradoxical effects of biochar on trace element dynamics can be explained by the complex interactions between biochar, soil chemistry, and plant physiological responses. Although biochar reduces overall trace element concentrations in soil through sorption and pH modification (Ibrahim et al., 2022; Natasha et al., 2022), plants respond through complex mechanisms involving both physiological adaptations and biochar-soil interactions, which enhance the TI (Figure 2), BI (Figure 3), and PI (Figure 4) of essential micronutrients relative to toxic elements. For essential micronutrients (Fe, Mn, Cu, Zn), plants likely activate compensatory

mechanisms including morphological modifications (reduced shoot branching, enhanced root architecture), biochemical changes (increased transporter expression, enzyme secretion), and enhanced rhizosphere interactions (microbial symbiosis, organic acid secretion) to upregulate their nutrient uptake systems (Francis et al., 2023; Pierik et al., 2013). These adaptations improve uptake efficiency and root-to-shoot translocation, reflected through TI (Figure 2), leading to a higher BI (Figure 3), compared with toxic elements. In contrast, for toxic elements (Cd, Pb, Co, Ni), plants may adopt avoidance strategies or may not activate mechanisms similar to those used for micronutrients to limit heavy metal uptake and translocation. The toxic-element uptake-limiting mechanisms of plants may include root exudation, rhizosphere modification, exclusion barriers, mycorrhizal associations, and cell wall binding, collectively serving as the first line



**Figure 5.** Hazard index (HI) of the micronutrients (A) and toxic elements (B) in five treatments and two seasons. Within a panel, data attached with the same letters are not statistically significantly different, with  $p \leq .05$ . Error bars indicate the SD of the means.



**Figure 6.** The relationship between heavy metal pollution index (HPI) and four calculated indices for micronutrient and toxic element groups: (a) bioaccumulation index (BI), translocation index (TI), and phytoextraction potential index (PI) for micronutrient groups (MN-BI, MN-TI, MN-PI); (b) BI, TI, and PI for toxic element groups (TX-BI, TX-TI, TX-PI); (c) hazard index (HI) for the micronutrient group (MN-HI); and (d) HI for the toxic element group (TX-HI).

of defense against heavy metal toxicity (Emamverdian et al., 2015; Yan et al., 2020). Biochar's surface functional groups and their effects on soil chemistry (pH modification, altered microbial activity) likely interact with these plant responses, enhancing selective nutrient acquisition while lowering toxic element uptake. However, these hypothesized explanations require further research to distinguish the relative contributions of plant physiological responses vs. biochar-mediated soil modifications as well as to fully understand the underlying mechanisms discussed above through molecular and rhizosphere studies.

Although the four TEs in the micronutrient group are essential for plant growth, they can cause phytotoxicity in rice at high concentrations, similar to toxic elements (Arif et al., 2016). To mitigate the adverse impacts of excess TEs, plants regulate the transport of these elements from roots to aboveground parts through metal chelation within the roots (Sebastian & Prasad, 2015). This process appears to have occurred in rice plants in our study, as we observed that the translocation index of both elemental groups was below 1, especially for the toxic element group (Figure 2). This finding indicates that rice plants absorbed both micronutrients and toxic elements into their roots but selectively translocated a larger proportion of micronutrients to aboveground parts compared with toxic elements. This observation aligns with Satpathy et al. (2014), who reported higher accumulation of micronutrients in rice tissues compared with nonessential toxic heavy metals. This differential translocation demonstrates the plant's sophisticated transport mechanism, which prioritizes essential micronutrients while restricting the movement of potentially harmful toxic elements. This selective translocation is a crucial adaptation that allows rice plants to maintain optimal nutrient balance while minimizing potential damage from toxic elements.

The BI values, an indicator measuring the extent of TE accumulation in rice tissues relative to soil concentration, were greater than 1 for both TE groups, indicating that rice's aboveground parts accumulate TEs beyond root absorption. Higher BI values for micronutrients (3.10 to 4.44) compared with toxic elements (1.38 to 1.71) suggest that rice preferentially accumulates essential micronutrients over harmful elements. This selective accumulation demonstrates the plant's ability to discriminate between essential and potentially toxic elements, aligning with our observations of translocation indexes. Aziz et al. (2023) reported consistently lower content of the toxic element Pb in rice plants compared with essential micronutrients Zn and Cu. Similarly, the findings from Hasan et al. (2022) supported the preferential bioaccumulation of micronutrients in rice tissues over toxic elements. This preference likely helps rice meet nutritional needs while minimizing exposure to toxic elements.

The PI measures the degree of TE removal from soil via plant absorption (Suman et al., 2018). For rice and other food crops, a high PI signals significant TE contamination in the plant, posing health risks, whereas a low PI indicates poor soil remediation. In this study, PI is determined by two factors, TE concentration in rice tissues and total rice biomass per ha. Biochar reduced TE levels in rice (see online supplementary material Figures 2–4) while increasing biomass and yield (data not presented in this study), consistent with numerous studies (Bagheri Novair et al., 2023; Liang et al., 2024; Liu et al., 2022). Consequently, biochar application, particularly rice-husk biochar during the dry season, increased PI for both TE groups (Figure 4). This demonstrates biochar's ability to lower TE concentrations in rice grain, reducing health risks, while improving soil remediation. This dual

effect highlights biochar's potential as a valuable tool in sustainable agriculture and environmental remediation.

Seasonal influences on trace element dynamics showed varying patterns across different indices. The HPI and TI demonstrated no clear seasonal trends for either micronutrients or toxic elements. However, pronounced seasonal effects were observed in both the PI and HI, with significantly higher values recorded during the dry season compared with the rainy season for both element groups (Figures 4 and 5). The elevated PI values during the dry season can be attributed to several factors. The index, calculated based on trace element concentrations and total rice biomass production, showed notably higher values in biochar-amended soils compared with control treatments. This enhanced efficiency of biochar during the dry season stems from multiple mechanisms. Biochar's high porosity and surface area improve soil water retention and availability during water-limited conditions (Razzaghi et al., 2020; Seyedsadr et al., 2022), maintaining stable growing conditions and supporting higher biomass production. Additionally, biochar enhances soil moisture conditions in water-stressed environments (Yoo et al., 2020), leading to improved nutrient availability and uptake efficiency. The modification of soil physical properties through biochar addition, including reduced bulk density and increased porosity, creates optimal conditions for root development and nutrient acquisition, ultimately enhancing biomass production (Murtaza et al., 2021). Similarly, the higher HI values observed in the dry season for both micronutrients and toxic elements can be explained through several interrelated mechanisms. Reduced soil moisture during the dry season results in more concentrated soil solutions, increasing dissolved ion concentrations and enhancing root-soil element contact. Water stress conditions alter plant mechanisms for water and nutrient transport from roots to aboveground parts, particularly to grains, leading to higher element accumulation. The oxidizing conditions prevalent in the dry season can increase soil element mobility (De Jonge et al., 2012), enhancing plant uptake and accumulation. Conversely, the abundant water during the rainy season creates a dilution effect on soil solution element concentrations, while reducing conditions may decrease element mobility, resulting in lower grain accumulation and reduced HI values. These seasonal variations in element dynamics emphasize the importance of considering temporal factors in agricultural management strategies and health risk assessments related to grain consumption.

### Implications for public health

The TE accumulation in rice grains poses potential health risks to consumers due to metal toxicity (Sarkar et al., 2023). Although humans can be exposed to heavy metals through various routes, daily dietary intake can account for up to 90% of the risk of toxic effects on human health (Guo et al., 2020a). A significant finding in this study is that biochar, while increasing the TE phytoextraction potential, simultaneously reduces the HI for human health, particularly in T3 (Figure 5). This result supports our final hypothesis that biochar reduces the human health risk associated with TE contamination from rice consumption. In this study, HI values fall within the range reported by Kelle et al. (2022), varying from 1.2 to 9.31. According to USEPA guidelines, HI values greater than 1 indicate potential noncarcinogenic risks for consumers (Zhao et al., 2023b). The HI is determined by two key factors, EDI and HQ, calculated for eight TEs categorized into micronutrient and toxic element groups. The observed HI difference between these groups reflects rice's preferential bioaccumulation and translocation of micronutrients over toxic elements (Figures 2 and 3). Notably, biochar application effectively reduced

exchangeable metal concentrations in soil, lowering EDI and HQ values and consequently decreasing HI values in biochar-treated plots. This effect was most pronounced in T3 (20 tons per ha rice-husk biochar), demonstrating biochar's dual potential to mitigate health risks from TE contamination in rice while enhancing soil remediation.

In this study, Fe and Pb were identified as the main contributors to health risks from rice consumption. The HI values for micronutrients were high (9.87–12.65), largely due to Fe's HQ (9.42–12.20). Excluding Fe, total HI values (2.98–3.95) were similar to those of toxic elements. Although Fe is essential, excess can cause tissue damage (Abbaspour et al., 2014; Charlebois & Pantopoulos, 2023). Another significant contributor to HI was Pb, with HQ values ranging from 0.99–1.6 (Table 4). These values are relatively high compared with some studies (Guo et al., 2022), but lower than others (Niknejad et al., 2024). At these levels, consumers may face a noncarcinogenic risk (Guo et al., 2022). Lead's toxicity affects multiple body systems, including renal, cardiovascular, and nervous systems (Kumar et al., 2022). It is also one of the heavy metals with high HQ values in rice grains reported in Chinese publications (Kong et al., 2018). Notably, biochar application, especially T3, reduced HQ values for Fe and Pb by decreasing their exchangeable soil contents (Acosta-Luque et al., 2023; Tusar et al., 2023). These findings underscore the complex relationship between soil amendments, plant uptake, and human health risks in rice cultivation.

### Management implication and limitations of the current study

The study demonstrates the dual benefits of biochar in rice cultivation. Biochar enhances rice's ability to extract TEs, improving soil quality, while reducing TE concentrations in rice grains, thereby lowering health risks. The improved phytoextraction potential is linked to enhanced rice growth due to biochar, with increased straw biomass crucial for extracting trace metals from soil. Concurrently, biochar's ability to reduce TE bioavailability in soil leads to lower concentrations in rice grains. The TEs accumulated in rice straw can be managed through various methods, such as energy production, used as a substrate for growing other crops, or returning it to rice fields with low TE content. The reduced TE concentration in rice grains is a key factor in decreasing the HI and potential human health risks. Furthermore, the conversion of rice straw, rice husks, and other agricultural by-products into biochar offers additional benefits, including effective management of agricultural wastes and increased added value.

The rice crop shows adaptive responses to biochar's effects on TE uptake. Figure 6B reveals an inverse relationship between the TX-HPI and the TX-BI and TX-HI indices, indicating that rice may limit toxic element uptake in stems and grains. However, this inverse relationship is absent for micronutrients, suggesting a different uptake mechanism. When soil micronutrient levels are low, rice seems to increase their uptake and translocation to aboveground parts, as supported by Figures 2 and 3, which show higher translocation and bioaccumulation of micronutrients compared with toxic elements when biochar reduces soil micronutrient content. These findings suggest rice balances nutritional needs while minimizing toxic exposure. However, this selective translocation and accumulation could pose challenges if micronutrient levels exceed safe limits. This implies that consumer health concerns may require prioritizing micronutrient accumulation over toxic element exposure. Further research is required to confirm these observations across different TE groups in rice.

This study, while significant, has limitations that highlight important avenues for further research. The small-scale and two-growing season field experiment may limit the generalizability of the findings to larger agricultural systems. Additionally, the distinct effects of the two biochar types used require further exploration. Although the application of 20 tons per ha of rice-husk biochar (T3) produced the most favorable results, longan-derived biochar also demonstrated unique benefits. This study primarily assessed the technical effectiveness of biochar application and therefore does not include a cost-benefit analysis of its use. However, applying 20 tons of biochar per ha could significantly increase production costs, potentially reducing the economic viability for rice farmers. Moreover, using 20 tons of biochar produced at 400–450°C may be technically and economically impractical, raising concerns about the feasibility and long-term sustainability of this approach. Instead, farmers could adopt a gradual application strategy, applying a few tons per ha per rice season and continuing this practice over multiple years to eventually reach the 20 ton/ha target or more. This incremental approach is highly feasible, as biochar is stable in the soil, provides long-lasting agronomic benefits, and can be produced on a small scale by individual farmers. As a result, it represents a practical and sustainable method for integrating biochar into rice production systems.

Another area requiring investigation is the mechanism behind rice plant responses to biochar-induced changes. Although biochar reduces the bioavailability of TEs, rice plants may develop compensatory mechanisms to enhance micronutrient uptake—an intriguing phenomenon that warrants deeper study. Additionally, the HI values for micronutrients compared with toxic elements may stem from outdated reference values used in the calculations, suggesting a need to revisit these benchmarks. Despite these limitations, the study provides valuable insights and suggests critical directions for future research. Future studies should focus on (1) long-term field trials to evaluate the durability of biochar's effects across multiple growing seasons, (2) cost-benefit analyses of different biochar types and application rates to determine the most economically viable options for farmers, (3) investigation of potential interactions between biochar and conventional fertilizers to develop integrated soil management strategies, and (4) examination of biochar effects on grain quality parameters beyond trace element content. Given that the optimal use of biochar may vary based on site-specific conditions, further research is also essential to enhance its benefits across diverse agricultural environments and to evaluate its long-term sustainability and ecological impact. Moreover, future research should use sequential extraction techniques for soil samples and specific tissue extraction methods to determine various chemical forms (water-soluble, exchangeable, carbonate-bound, oxide-bound, organic-bound, and residual fractions) of TEs in soil and different plant tissues, which provide deeper insights into their bioavailability and translocation mechanisms.

### Conclusion

The study shows that biochar application significantly reduces exchangeable TEs in soil, with the greatest reduction in Treatment 3 (20 tons of rice-husk biochar). This leads to a lower HPI, particularly for micronutrients, which were notably lower than toxic elements. In response to reduced micronutrient availability, rice plants seem to enhance the uptake and accumulation of micronutrients in aboveground parts, a response not seen for toxic elements. This increased uptake raises the HI for

micronutrients compared with toxic elements. However, biochar still effectively reduces the HI for both TE groups, lowering health risks compared with nonbiochar treatments. The study also found a strong negative correlation between HPI and both the BI and HI for toxic elements but not for micronutrients. Overall, biochar's dual role in promoting TE phytoextraction while minimizing health risks underscores its potential as a sustainable and effective strategy for mitigating trace metal contamination in rice production and safeguarding human health. These findings demonstrate that converting agricultural waste to biochar for rice production offers farmers several practical benefits, including enhanced food safety through reduced toxic elements, cost-effective soil management, and reduced health risks from contaminated rice consumption, collectively contributing to more sustainable and profitable rice cultivation. However, a major limitation of this study is that applying 20 tons of biochar per ha is a considerable quantity, which may render this method impractical and unsustainable. A more viable alternative is a gradual biochar application strategy, where smaller amounts are applied per rice season and continued over multiple seasons until reaching 20 tons per ha, thereby enhancing the long-term sustainability of this approach. Nevertheless, further research is needed to evaluate the effectiveness of these strategies. Additionally, a comprehensive cost-benefit analysis of biochar application should be conducted to assess its economic feasibility in rice production. Other studies in the future should also focus on long-term field trials, interactions between biochar and conventional fertilizers, and the utilization of locally available biomass for biochar production, aiming to optimize benefits across different agricultural regions.

## Supplementary material

Supplementary material is available online at *Integrated Environmental Assessment and Management*.

## Data availability

Data, associated metadata, and calculation tools are available from the corresponding author Binh Thanh Nguyen ([nguyenbinh@iuh.edu.vn](mailto:nguyenbinh@iuh.edu.vn)).

## Author contributions

Hao Phu Dong (Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Writing – original draft), Binh Thanh Nguyen (Conceptualization, Funding acquisition, Methodology, Software, Supervision, Writing – review & editing), Thia Hong Le (Conceptualization, Funding acquisition, Resources, Writing – original draft), My Hoang Dang (Data curation, Formal analysis, Funding acquisition), and Anh Hoang Le (Investigation, Methodology, Supervision, Writing – original draft)

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## Conflicts of interest

The authors have no conflict of interest to declare.

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