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Original Article

Phytoavailability and Mobility of Heavy Metals in Oil Refinery-Polluted Soil Amended with Olive Waste Biochar and Maize (*Zea mays* L.) Cultivation

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ABSTRACT

The accumulation of heavy metals in the soil surrounding oil refineries is a major environmental and agricultural issue, demanding effective and environmentally friendly cleanup methods. This study was conducted to determine the effectiveness of olive waste biochar (OWB) in reducing the bioavailability of these heavy metals, ultimately assessing its potential as a sustainable remediation strategy for polluted environments, particularly in soils near an oil refinery. A 75-day pot experiment was conducted using maize (*Zea mays* L.) to evaluate heavy metal uptake, as this duration provides for adequate root development and translocation mechanisms, the experiment was conducted through a randomised complete block design after olive waste biochar preparation by pyrolysis at 500 to 600°C (Setting the pyrolysis temperature at 500-600 °C due to this range is widely recognized as optimal for producing high-quality biochar that is suitable for environmental remediation). In addition, OWB was added to soil at the rate 0% (control), 2.5%, 5%, 7.5%, and 10% (w/w). Heavy metal concentrations in both soil and maize tissues were quantified using inductively coupled plasma optical emission spectrometry (ICP-OES). The use of olive waste biochar at different application rates successfully ($P < 0.05$) affected soil phytoavailability and immobilization of all studied heavy metals. The results showed inverse relationships in terms of heavy metal accumulation in plant tissues. When Zn being most taken up, followed by Cr and Ni and finally Fe, with reductions of 62.68%, 59.1%, 46.15%, and 32.26%, respectively. Heavy metal immobilisation in soil exhibited different patterns, with a tendency of Zn > Cr > Ni > Fe. The optimal reduction in metal uptake and highest immobilization occurred at the 10% OWB application level. The findings have proven that OWB functions effectively as an environmental sustainability measure for handling heavy metal contamination in soil.

Keywords: Heavy metal; immobilization; Phytoavailbility; Olive Waste; Biochar.

1 Introduction

Heavy metals, including iron (Fe), chromium (Cr), zinc (Zn), and nickel (Ni), are frequently found in soil because of different human activities, including mining, industrial discharges, agricultural practices, and poor waste management [1]. These metals are non-biodegradable, meaning they can remain in the environment for long periods, posing considerable risks to human health, agricultural productivity, and ecosystems [2]. The issue of heavy metal contamination is particularly serious in places near oil refineries. Numerous pollutants, including heavy metals, are created during oil extraction and refining operations and can contaminate surrounding soils, rivers, and groundwater [3]. In addition to lowering fertility and degrading soil quality, this pollution can cause toxic metals to bioaccumulate in crops [4]. Therefore, preserving environmental sustainability and safeguarding human health depend on reducing heavy metal pollution. This underscores the urgent need for effective soil remediation techniques that can stabilize heavy metals and reduce their phytoavailability, ensuring sustainable land use and public health protection [5]. Traditional soil remediation techniques, such as excavation and chemical treatments, are often costly and labour-intensive. However, these approaches may not be environmentally sustainable or economically feasible for large-scale applications [6]. This has driven interest in more sustainable, environmentally friendly, and cost-effective solutions, such as biochar derived from organic waste materials. Biochar, a carbon-rich product obtained through biomass pyrolysis, has gained attention for its potential to enhance soil health, improve nutrient availability, and immobilize contaminants [7] Biochar can be made from various waste products, such as wood chips, sewage sludge, and agricultural waste. It is a sustainable and environmentally friendly solution for pollution, as it repurposes waste and improves soil quality. Its high surface area and porous

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structure enable it to effectively bind heavy metals [8]. Since feedstock strongly influences the physical and chemical properties of biochar, utilizing abundant local agro-wastes is recommended to reduce production costs and manage organic waste effectively. In this study, prepared biochar from olive waste was used due to the availability of huge raw materials in the study area. In addition, previous studies used Olive Waste Biochar (OWB), produced from olive waste, as an innovative approach to addressing heavy metal pollution [9-10]. By decreasing phytoavailability, OWB can support plant growth in contaminated soils, minimizing the risk of metal translocation [11]. This is particularly significant for areas like the Koya District, where agricultural activities may be impacted by industrial pollution. Applying biochar made from olive waste not only provides the dual benefit of waste management and soil treatment but also aligns with the principles of a circular economy, promoting sustainable agricultural practices[12]. As awareness of sustainable land management grows, integrating biochar into remediation strategies represents a practical step forward [13]. In this study, Maize (*Zea mays* L.) was chosen as a test plant and bioindicator to examine the uptake of heavy metals and phytoavailability because of its high biomass generation, tolerance of mild pollution, and extensive root system that supports rhizofiltration and root-to-shoot translocation mechanisms, which are critical for assessing metal stabilization efficacy [14]. Previous and contemporary research have shown its efficacy in phytoremediation for heavy metals such as Pb, Cd, Cr, and Cu [15-17], emphasizing its dual importance in environmental protection and food security. To our knowledge, the effect of olive waste biochar (OWB) on the immobilization and phytoavailability of studied heavy metals under maize cultivation has not been documented adequately in the study area. Therefore, a pot experiment was set up to understand the effectiveness of OWB in stabilizing heavy metals (Zinc (Zn), Chromium (Cr), Nickel (Ni), and Iron (Fe)) in polluted soils. Moreover, this study also examines its impact on metal phytoavailability and evaluates its implications for soil rehabilitation and sustainable agriculture.

2 Materials and Methods

2.1 Soil sample preparation and analyses

Approximately 300 kg of surface soil from the waste (oil factory) site samples (0–30 cm depth) were collected randomly from 5 different places by using an auger, which is located in the west of Koya District, Iraq (44.550648E and 36.072323N), as shown in Figure 1. Samples were mixed thoroughly and air-dried, and then to remove stones and debris, the soil samples were crushed and sieved through a 2 mm sieve. The hydrometer method, as described by Beretta *et al.* [18]. It was employed to determine soil particle size distribution. The pH and EC of soil samples were measured from the suspension of a 1:2.5 (w/v) soil/ distilled water ratio by using a HANA pH-meter, Model pH211, and an EC meter HANNA HI 98304, respectively [19]. A 0.5 g subsample of the sieved soil was digested using 2 ml of 30% hydrogen peroxide (H_2O_2) and 6 mL of 65% nitric acid (HNO_3) in a 100 ml digestion tube. The digestion was carried out by heating the mixture in a hot block digester for 45 minutes, following the method described by [20] The analysis of total nitrogen (N) was found by using the Kjeldahl method (model K-350, Germany), whereas total phosphorus (P) and magnesium (Mg) were measured by a spectrophotometer model UV-9200. Heavy metals such as Fe, Cr, Ni, and Zn were analyzed through Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Calcium (Ca^{2+}), Sodium (Na^+), and Potassium (K^+) were determined using a flame photometer (Model BWB XP, United Kingdom) [21].

Table 1: The selected physicochemical properties of the studied soil (mean n=3).

Parameters	Value	Parameters	Value
Clay (%)	41.00 ±0.57	Total Na (%)	0.001±0.0001
Silt (%)	35.66 ±0.66	Total Ca (%)	0.016±0.002
Sand (%)	23.33 ±0.33	Total Mg (%)	0.005±0.003
Texture (USDA)	Silty Clay	Total Cd (mg kg^{-1})	1.08±0.011
Moisture content (%)	2.2 ±0.11	Total Fe (mg kg^{-1})	8050±28
pH	6.13 ±0.088	Total Cr (mg kg^{-1})	619.12±3.88
EC (mS m^{-1})	0.25 ±0.017	Total Ni (mg kg^{-1})	189.56±0.78
Total N (%)	0.004 ±0.0002	Total Cu (mg kg^{-1})	38.33±1.45
Total P (%)	0.0004 ±0.00006	Total Zn (mg kg^{-1})	369.55±1.90
Total K (%)	0.032±0.001	Total Pb (mg kg^{-1})	2.69±0.11
		Total V (mg kg^{-1})	80.59±0.18

Mean of three replicates ± SE.

2. 2 Biochar preparation and characterization

2. 2. 1 Biochar Preparation

The first step: 100 kg of olive waste (OW) was collected as the feedstock material for biochar production. The olive residues were sun-dried during the summer months (ambient temperature > 45 °C) and required no further grinding, as they were already in small pieces.

The second step: preparing biochar was using a locally fabricated double-barrel pyrolysis system, following the method described by Lamichhane *et al.* [22]. The machine has two barrels: a little one that holds 35 gallons and a huge one that holds 60 gallons.

Third and final step: The biochar production process in this study used a method reported by Li *et al.* [23]. Pyrolysis was conducted at temperatures ranging from 500 to 600 °C for 2 hours. The barrel inside was filled with biomass, undergoing pyrolysis because the barrels prevent the burning of (OW). A laser thermometer was continuously used to maintain the pyrolysis temperature at 500-600°C (model UNI-T UT306S). The total process check was 24 hours from pyrolysis to cooling, as described in Ferraro *et al.* [24]. And the final product was made, and then biochar was passed through 100 mesh (model LC-dolida 100 Mesh) sieves to collect a fine fraction of OWB.

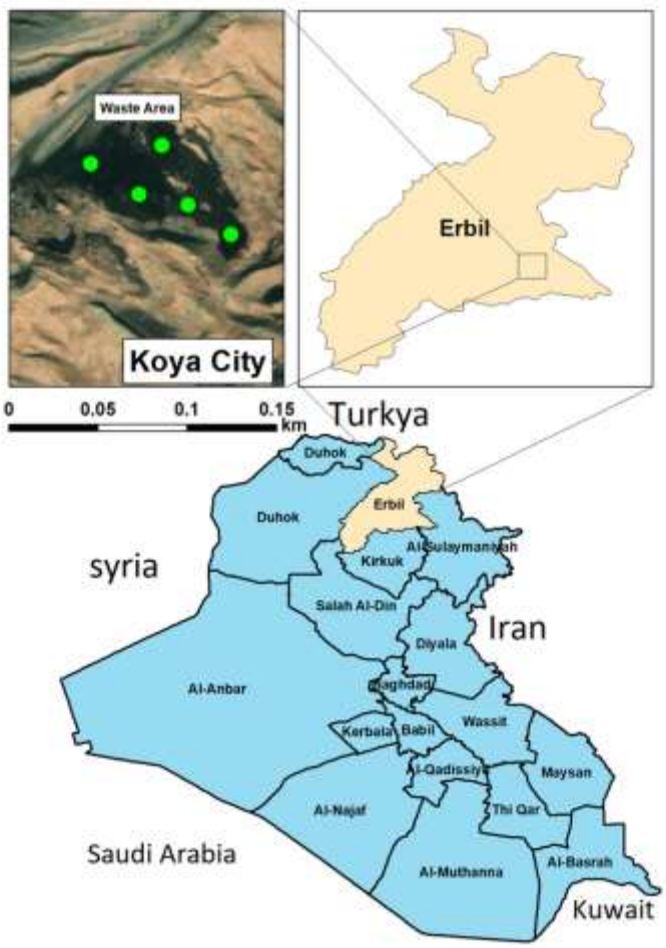

Figure 1: Location map of the waste area of Koya.

2. 2. 2 Characterization of Biochar

The physicochemical properties of the OW biochar were determined by following the standard procedures. The pH and EC were measured from saturated paste extract by using an ALLa pH meter (model pH SX-610) and a HANNA EC meter (model HI 98304), respectively [25]. Moisture content was determined by drying 5 g of the biochar sample at 100 °C for 10 minutes using an auto moisture analyser (Ohaus Model MB45, Switzerland). The amount of ash was determined using dry combustion by muffle furnace (KSL-1000X Materials Technology International, Uniteds) [26]. The Walkley-Black protocol was applied to determine the total C content, as described in Allison [27]. Cation exchange capacity was measured using the 1N NH_4OAc buffered at pH seven technique as described by Sikora and Moore [28]. Surface area analysis was conducted using a Quantachrome surface area analyser (AS1Win™, Version 2.01) through nitrogen (N_2) adsorption at 77.3 K. Prior to analysis, samples were degassed at 100 °C for 9 hours. The Brunauer–Emmett–Teller (BET) method was applied to calculate the specific surface area, while pore volume, pore radius, and internal surface area were obtained from desorption isotherms using the Barrett–Joyner–Halenda (BJH) method. Monolayer adsorption capacity was derived using four relative pressure points ($P/P_0 = 0.05–0.3$), and total pore volume was calculated at a relative pressure of approximately 0.97, as described by Claoston *et al.* [29]. Biochar samples were sieved to 1 mm for elemental analysis; 0.25 g of biochar was digested in a 100 mL tube with 2 mL of 30% H_2O_2 and 6 mL of 65% HNO_3. The biochar was then heated in a hot block digester for 45 minutes as described in Tariq *et al.* [30]. The Kjeldahl technique (model K-350, Germany) was used to analyze the total nitrogen (N) as described in Temai *et al.* [31], whereas total phosphorus (P) and magnesium (Mg) were measured by a spectrophotometer model UV-9200 as described in Bah *et al.* [32]. Using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), for measuring heavy metals concentrations including Cd, Cr, Ni, Cu, Zn, and Pb as described in Lu *et al.* [33], while cations of Ca^{2+}, Na^+, and K^+ were measured using a flame photometer (model BWB XP,K) [34].

2. 3 Pot Experiment:

A pot experiment was conducted during the summer of 2024 at the Koya Forest Nursery (latitude 36.093765°N, longitude 44.667702°E). Each plastic pot (25 cm height, 25 cm top diameter, and 15 cm bottom diameter) was filled with 7 kg of a soil mixture amended with different application rates of olive waste biochar (OWB): 0%, 2.5%, 5%, 7.5%, and 10% w/w, corresponding to 0.000, 0.175, 0.350, 0.520, and 0.700 kg OWB per pot, respectively. To prevent leachate loss, plastic cups were placed underneath each pot. The amended soils were undisturbed for 7 days to homogenize and reach equilibrium. During this equilibration period, the moisture content of all pots was maintained at 70% of field capacity by daily monitoring and adjusting the water content. After equilibration, three maize seeds (Zea mays L.) were sown in each pot, following standard pot experiment protocols in maize cultivation [35]. When planting, a uniform application of NPK fertilizer at a rate equivalent to 150 kg/ha was applied to all pots. Following germination, seedlings were thinned to retain two plants per pot. The plants were grown for 75 days, with moisture content maintained daily through regular irrigation based on visual assessment and soil moisture conditions. The experiment was arranged in a completely randomized design (RCRD) with three replications. After 75 days of growth, plants were harvested. Shoots and roots were separated, washed thoroughly with distilled water to remove adhered soil particles, and then oven-dried at 70 °C for 42 hours to determine dry biomass. For heavy metal analysis (Fe, Ni, Cr, and Zn), approximately 0.5 g of ground plant tissue was digested with 6 mL of 65% HNO_3 and 2 mL of 30% H_2O_2. The digested samples were cooled and diluted to 50 mL with distilled water. The metal concentrations were determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; Perkin Elmer Optima 2100 DV) [36].Soil samples were also collected after harvesting to determine the immobility of heavy metals in the soil after the digestion of the soil samples, as mentioned previously.

The phytoavailability of heavy metals was calculated by the following equation (1), as described in Cao *et al.* [37].

$$\text{Phytoavailbility}(\%) = \frac{\text{heavy metal concentration (mg/kg) in plant} \times \text{above ground biomass (kg/pot)}}{\text{heavy metal (mg/kg) in soil} \times \text{soil mass (kg/pot)}} \quad (1)$$

The immobility of heavy metals in soil was calculated following Equation (2), as reported by Park *et al.* [38]:

$$\text{Immobilization of Heavy metals}(\%) = \frac{\text{heavy metal for the control (mg /kg)} - \text{heavy metal in biochar treated sampl (mg /kg)}}{\text{heavy metal (control)(mg /kg)}} \times 100 \quad (2)$$

2. 4 Statistical Analysis:

All data were checked for normality and homogeneity of variances before statistical analysis. The precision of the data was calculated and expressed as standard deviation (SD) and standard error. Subsequently, the data underwent statistical analysis of variance (ANOVA) using SPSS version 26 at the 5% significance level, and the Duncan test was utilized for mean separation [39].

3 Results and Discussion

3. 1 Olive Waste Biochar Properties

The physicochemical properties of the olive waste biochar (OWB) are presented in Table 2. The OWB exhibited an alkaline pH of 8.0 and an electrical conductivity (EC) of 2.16 mS cm^{-1}. The cation exchange capacity (CEC) has a value of 89.26 $cmol^{+}$ kg^{-1}, the result is consistent with Ibrahim and Tariq. [40].which reflects the material's ability to retain and supply cationic nutrients in the soil [41]. The elemental composition of OWB followed the descending order: N > Ca > K > P > Na > Mg, with mean concentrations of 1.39%, 1.33%, 0.82%, 0.57%, 0.02%, and 0.012%, respectively. The result is consistent with Wan Azlina et al. [42]The carbon content was 67.94%, the ash content was 5.73%, and the percentage of volatile matter was 24.73%. The BET specific surface area of the OWB was 17.997 m^2/g, while the total pore volume was 0.043 cm^3/g. Despite this number is not exceptionally high, it does add to biochar's adsorption capacity, especially when combined with other parameters such as surface functional groups, pore structure, and high pH, all of which impact heavy metal sorption. According to a study by Ahmad et al. [43], both surface area and chemical characteristics are significant in metal immobility.The result is consistent with Ghani et al. [44]. Due to its high surface area, OWB is much more suitable for adsorption [45]. OWB contained low concentrations of heavy metals, all of which were below regulatory limits for soil amendments [46].Indicating its suitability for environmental application.

Table 2: The selected physicochemical properties of OWB (mean n=3).

Parameters	Value
Moisture content %	2.32±0.17
PH	8±0.11
EC (mS cm^{-1})	2.16±0.01
Volatile Matter %	24.73±0.145
Carbon content %	67.94±0.9
Ash Content %	5.73±0.17
CEC ($cmol^{(+)}$ kg^{-1})	89±2.6
Total N (%)	1.39±0.049
Total P (%)	0.57±0.006
Total K (%)	0.82±0.02
Total Na (%)	0.02±0.003
Total Ca (%)	1.33±0.06
Total Mg (%)	0.012±0.0007
Total Cd (mg kg^{-1})	0.00036±0.000006
Total Cr (mg kg^{-1})	0.00012±00.000002
Total Ni (mg kg^{-1})	0.00036±0.000004
Total Cu (mg kg^{-1}))	0.00023±0.000002
Total Zn (mg kg^{-1})	0.00014±0.000001
Total Pb (mg kg^{-1})	0.00054±0.000005
Total surface area BET (m^2g^{-1})	17.997
Pore volume (cm^3g^{-1})	0.043
Pore radius (A°)	17.57

Mean of three replicates ±SE

3. 2 Heavy Metal Concentrations in Maize Plants and Soil

Figs. 2 and 3 show the Fe, Zn, Cr, and Ni concentrations in the roots and shoots of maize plants produced in polluted soil treated with varying quantities of olive waste biochar (OWB). The results demonstrated that the concentrations of heavy metals in both components dramatically dropped with increasing levels of OWB. The lowest concentrations of Fe, Zn, Cr, and Ni (17, 20, 18, and 20 mg kg^{-1}) were recorded in samples treated with the highest level of OW biochar, 10%, respectively. The trends of reduction of Zn, Cr, Ni, and Fe by percentages as a result of the highest level of OWB application were as follows: 58.33%, 58.13%, 55.55%, and 54.05%, respectively, compared to the control. The results are in line with Yang *et al.* [47]. Similar trends were observed in the roots; the data revealed a notable decrease in heavy metal levels within plant roots as the percentage of olive waste biochar (OWB) increased. The lowest concentrations of Fe, Zn, Cr, and Ni (42, 25, 27, and 28 mg kg^{-1}) were recorded in samples treated with the highest level of OW biochar, 10%, respectively. The trends of reduction of Zn, Cr, Ni, and Fe by percentages as a result of the highest level of OWB application were as follows: 62.68%, 59.1%, 46.15%, and 32.26%, respectively, compared to the control. Figure 4 shows the Fe, Zn, Cr, and Ni concentrations in the soil after harvesting the plants. The lowest concentrations of Fe, Zn, Cr, and Ni (5400, 13.6, 14.2, and 25.6 mg kg^{-1}) were recorded in samples treated with the highest level of OW biochar, 10%, respectively. The trends of reduction of Zn, Cr, Ni, and Fe by percentages as a result of the highest level of OWB application were as follows: 63.24%, 35.45%, 30.81%, and 28.94%, respectively, compared to the control. The statistical results indicated that biochar consistently reduced soil Zn, Cr, Ni, and Fe concentrations at different rates. These reductions of heavy metals in plant parts and soil directly relate to the raise in pH and CEC that were observed after applying OWB. Previously, reports indicated that an increase in soil pH may make metal ions less available to plants, whereas higher CEC in the soil can help hold positive metal ions, making them move about less in the soil [48-49]. Furthermore, the findings of this study agree with earlier studies showing that the functional groups, porosity, and high surface area in biochar enable more adsorption and immobilization of heavy metals [50-51]. Since the metal oxide also has a high CEC and pH of 11.1, combined with a moderate BET surface area, it is suitable for this remediation process. The same results were also reported [52]. In addition, the concentrations of Fe, Zn, Cr, and Ni were markedly reduced in the shoots in comparison to the roots in all the treatments. The pattern reflects the idea that little metal moves from roots to shoots, a process slowed by plant physiological properties such as metal storage in root vacuoles and binding to the root cell wall. This is notably true for Cr and Fe, which are more securely linked to the xylem and end up in the roots, whereas Zn and Ni can circulate more freely throughout the plant, though they may still be constrained by the strong binds generated by biochar. As indicated in previous papers, heavy metal translocation from roots to shoots can be specific to each metal and can be decreased by biochar, which binds metals in the soil [38,53].This is consistent with previous studies that reported lower mobility and translocation of metals in the shoots of maize plants [38,54].

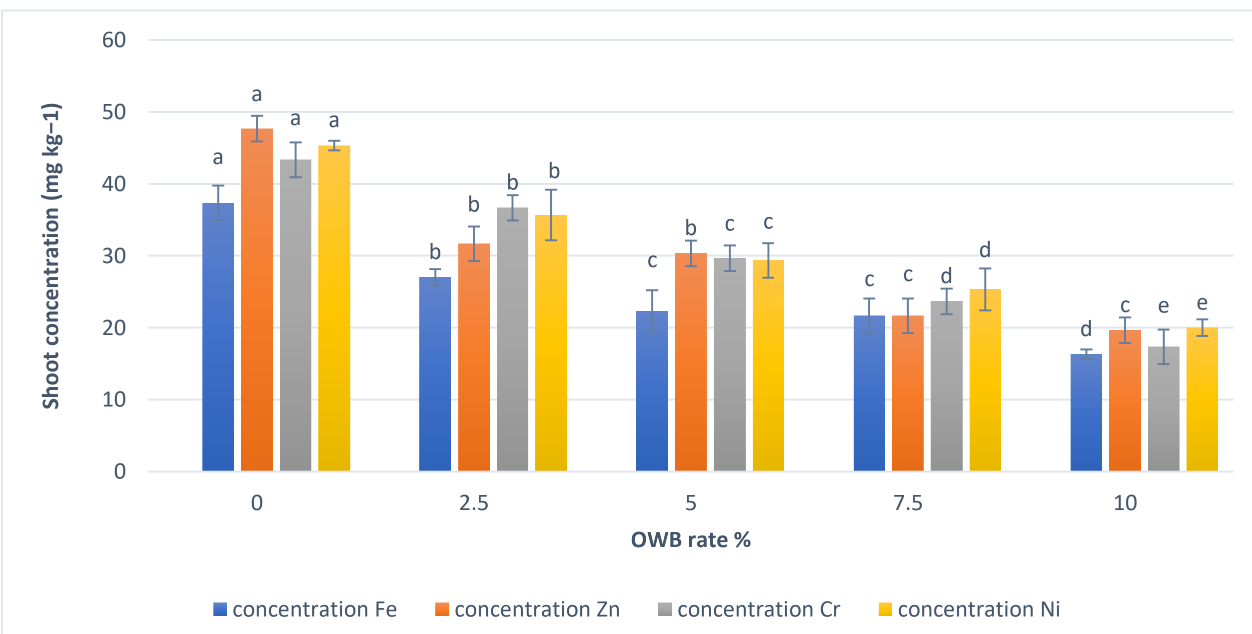

Figure 2: Concentration (mg kg−1) of Cr, Zn, Ni, and Fe in the Shoot of maize grown in polluted soil amended with OWB (mean n = 3, ±SE).

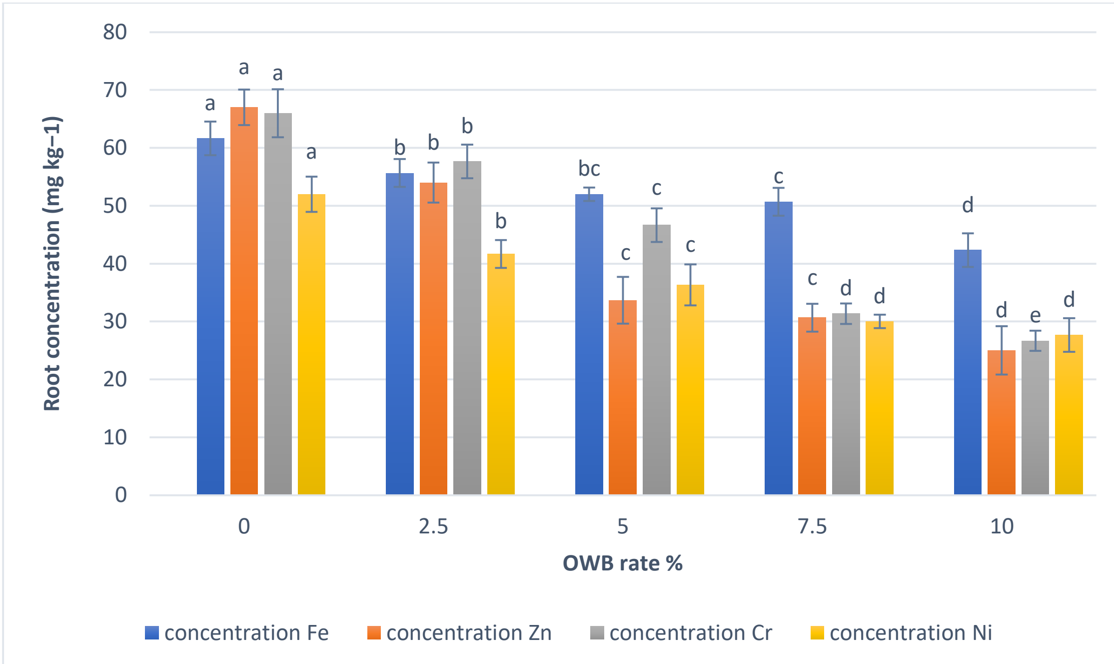

Figure 3: Concentration (mg kg−1) of Cr, Zn, Ni, and Fe in the root of maize grown in polluted soil amended with OWB (mean n = 3, ±SE).

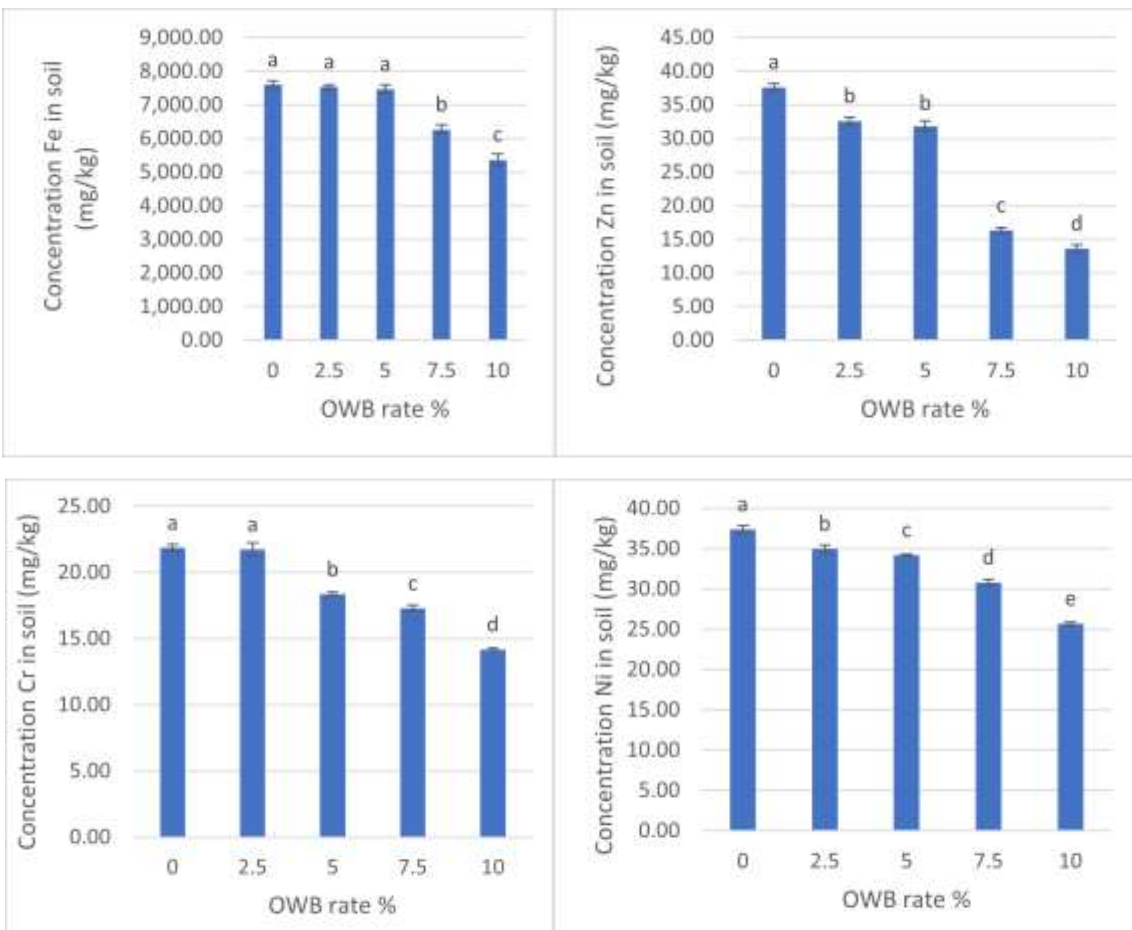

Figure 4: Concentration (mg kg−1) of Cr, Zn, Ni, and Fe in the soil of maize grown in polluted soil amended with OWB (mean n = 3, ±SE).

3. 3 Phytoavailability and Immobilization of Chromium (Cr), Zinc (Zn), Nickel (Ni), and Iron (Fe):

The phytoavailability results for heavy metals are presented in Table 3. The application of olive waste biochar (OWB) significantly ($p < 0.05$) reduced the phytoavailability of Cr, Zn, Ni, and Fe in the soil. Even at a low application rate of 2.5% (w/w), OWB effectively decreased the availability of these metals to maize plants. The most pronounced reductions were observed at the 10% OWB treatment. At this highest application level, phytoavailability of Ni, Zn, Cr, and Fe decreased by 66.31%, 68%, 69%, and 75%, respectively, compared to the untreated control. This finding is consistent with earlier studies that reported significant decreases in metal phytoavailability upon biochar application [37,55].

Table 3: The effect of biochar on the phytoavailability (%) of Chromium (Cr), Zinc (Zn), nickel (Ni), and Iron (Fe) in corn leaves.

Biochar rate (%)	Cr phytoavailability (%)	Ni phytoavailability (%)	Zn phytoavailability (%)	Fe phytoavailability (%)
Control	0.0055	0.0187	0.0101	0.0004
2.5	0.0040	0.0126	0.0058	0.0002
5	0.0031	0.0099	0.0053	0.0002
7.5	0.0023	0.0082	0.0036	0.0002
10	0.0017	0.0063	0.0032	0.0001

The immobilization rates of chromium (Cr), nickel (Ni), zinc (Zn), and iron (Fe) increased consistently with rising biochar application levels, as shown in Table 4. The highest immobilization was observed at the 10% biochar application rate. For chromium, the immobilization rate increased from 0.55% in soil treated with 2.5% OWB to 35.1% at the 10% application level. Nickel followed a similar pattern, with immobilization rising from 6.56% at 2.5% to 31.3% at 10%. Zinc exhibited the highest immobilization among the four metals, increasing from 13.34% at 2.5% to 63.82% at 10%. Iron also showed a marked increase, with immobilization rising from 0.88% to 29.39%. Alkaline nature and high surface reactivity as shown in Table 2, which enhance its metal adsorption capabilities. This is in agreement with the findings of [38,56].

Table 4: The effect of biochar on the immobilization (%) of Chromium (Cr), Zinc (Zn), Nickel (Ni), and Iron (Fe) in soil.

Biochar rate (%)	Cr Immobilization (%)	Ni Immobilization (%)	Zn Immobilization (%)	Fe Immobilization (%)
2.5	0.55	6.56	13.34	0.88
5	16.02	8.51	15.36	1.75
7.5	20.87	17.58	56.62	17.54
10	35.10	31.31	63.82	29.39

The immobilization effectiveness varied between metals, demonstrating metal-specific behaviour. The most immobilized element was zinc (up to 63.82% at 10% OWB), mainly for its high mobility and limited bonding with soil, leading to higher adsorption compared to others [38,48]. Thanks to the strong bond Cr has with oxygen-containing groups in biochar, only an average immobilization of 0.55% to 35.1% was observed [49]. The amount of nickel that was immobilized rose from 6.56% to 31.3% likely due to it bonding to biochar and forming precipitates as the pH increased. The immobilization of iron decreased from 0.88% to just 29.39%, probably due to it being bonded with soil minerals and having a lower way of dissolving [57]. The findings indicate that the mode and amount of metal immobilization by biochar are both dependent on its type and dosage.

Conclusions

This study shows that the addition of levels of OWB significantly decreases phytoavailability and increases the immobility of heavy metals in soil, thereby reducing their uptake by plants. Among the tested application rates, 10% OWB was found to be the most effective in immobilizing heavy metals, which resulted in substantial decreases in their concentrations in soil, plant roots, and shoot systems. The reduction in phytoavailability was particularly notable for Chromium, Nickel, Zinc, and Iron, demonstrating OWB's strong adsorption capacity. Additionally, the high carbon content, alkaline pH, and large surface area of OWB contributed to its superior performance as a soil amendment. These findings suggest that the application of 10% of OWB can enhance soil health and minimize environmental risks associated with heavy metal contamination. The findings of this experiment are highly encouraging; nonetheless, more field investigations are required to prove OWB's actual benefit as a remediation technique.

Data Availability

All data generated or analyzed during this study are included in the article.

Conflicts of Interest

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

Acknowledgment

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