**Dynamics of biochar on zinc and iron bioaccumulation in groundnut grown on contaminated soils in Amagu, Abakiliki Ebonyi State.**

**ABSTRACT**

The study evaluated the influence of biochar on heavy metal accumulation in the pods of groundnut cultivated in heavy metal-contaminated soils in Amagu, Abakiliki Ebonyi State. The soil samples were collected from farmlands adjacent to the mining sites located in Amagu, in Abakaliki Local Government Area of Ebonyi State. Bulked soil samples were air-dried and sieved using a 5mm sieve. 10 kg of air-dried soil was put in a 12-liter bucket; water was applied to moisten the soil at 60% field capacity. The experiment was a completely randomized design. Biochar was applied at 0, 20, 40, 60, and 80 t/ha. Groundnut seeds were planted two (2) weeks after biochar application. Soil samples were analyzed for physical and chemical properties before planting and after harvest. Data collected were subjected to analysis of variance (ANOVA) using GenStat. The results observed that biochar applied had different responses to Zn and Fe accumulation across the entire plant parts. It also revealed that the amount of Zn in soil ranged between 167mg/kg to 1750mg/kg, while Zn in shoot ranged between 67mg/kg to 1133mg/kg, Zn amount in the pod of groundnut ranged between 102mg/kg to 1482mg/kg, the results on Zn content in seeds of groundnuts ranged from 283mg/kg to 1586mg/kg. It was observed from the results, that concentration of Zn increased as biochar rates increased. The Fe concentration in the pod ranged from 1601mg/kg to 5668mg/kg, and the result on Fe content in seed ranged from 1705mg/kg to 11537mg/kg. Bioaccumulation factor (BAF) and Translocation factor (TF) were ≥1, thereby classifying groundnut as an effective hyperaccumulator. The application of this research finding would go a long way in improving food safety and human health.

**Keywords**: BAC, biochar, groundnut, heavy metal, iron, TF, zinc.

**INTRODUCTION**

The rapid increase in population, mechanization, mining, sewage sludge, industrial wastes, and intensive use of inorganic fertilizers and pesticides are among the causes of heavy metal pollution in the soil (Mazhar *et al.,* 2020; Irfan *et al.,* 2021). Heavy metals can be transferred from soil to plant tissues, thus adversely affecting plant growth and development, and even causing health problems for humans and animals when their byproducts are consumed. Zinc (Zn) is an essential micronutrient for plant growth and development, playing a crucial role in various enzymatic processes, photosynthesis, hormone regulation, and nutrient uptake (Gonmei *et al*., 2022). Without sufficient Zn, plants may exhibit stunted growth, chlorosis, and reduced yields. However, excessive accumulation of zinc in soil can result in significant environmental challenges, including a reduction in soil fertility and potential toxicity to both plants and microorganisms. This situation underscores the necessity for the implementation of effective remediation strategies aimed at mitigating its adverse effects (El-Sorogy *et al*., 2024, Kong *et al*., 2024; Sun *et al*., 2024). Excess Zn levels disrupt nutrient cycling and alter soil microbial communities, affecting ecosystem sustainability (Kalousek *et al*., 2024).

Zn and Iron (Fe) toxicity also negatively impacts microbial processes, affecting soil health (Anjum et al., 2024). Therefore, maintaining an optimal Zn and Fe level in plants and the environment is crucial for sustainable agriculture and ecological balance. Research has also indicated that Zn and Fe pollution in soil can affect the activities of soil microorganisms, causing ecological imbalances and soil degradation. Therefore, monitoring and controlling these metals in the soil are pertinent to protect the ecosystems and ensure the sustainable development of the agricultural sector. The impact of zinc and Iron pollution on ecosystems is a significant concern due to its potential hidden effects. Plant Zinc accumulation can lead to reduced growth, chlorosis, and even death. This is because excessive zinc interferes with the uptake and transport of essential nutrients, such as iron and manganese. Additionally, zinc pollution can disrupt the balance of microorganisms in the soil, affecting nutrient cycling and overall soil fertility (Koagouw *et al*., 2022). Zinc and Iron pollution can also affect animals, as it can accumulate in their tissues through the food chain. High levels of zinc and iron in animals can lead to reproductive and developmental issues, immune system suppression, and even death.

Biochar is recognized for its use as a soil amendment. It attracts heavy metals (lead, copper, zinc, chromium, cadmium, arsenic, etc.), prevents soil erosion, and increases soil pH, especially in acidic soils, due to its alkaline pH. Due to its cation exchange capacity, it improves the soil cation exchange capacity and increases soil fertility (Mansoor *et al.,* 2021; Salam, 2022). Biochar reduces toxic metal mobility in soil due to active functional groups such as carboxylic acid (–COOH), – C=O and inorganic ion (e.g., PO4) species it contains (Irfan *et al.,* 2021; Pan *et al*., 2021; Houssou *et al.,* 2022). Biochar application improves heavy metal-contaminated soil by preventing the leaching of heavy metals and reducing their availability by plants (Arshad *et al*., 2022; Houssou *et al*., 2022).

These organic materials immobilize heavy metals by different processes: by providing sorption capacity on negatively charged surfaces, by complexation with organic substances with a high molecular weight and by increasing the pH of the soil inducing precipitation of mineral phases and increasing the amount of negatively charged surfaces (Kasozi *et al.,* 2010; Beesley and Dickinson, 2011; Mohan *et al.,* 2014) as well as been responsible for the sorption of dissolved organic matter (DOM) and enhanced microbial activity.

Groundnut (*Arachis hypogaea*) is a [legume](https://en.wikipedia.org/wiki/Legume) [crop](https://en.wikipedia.org/wiki/Crop) grown in the [tropics](https://en.wikipedia.org/wiki/Tropics) and subtropics, important to both small and large commercial producers. It is classified as both a grain legume and, due to its high oil content, an oil crop.  Groundnut belongs to the botanical [family](https://en.wikipedia.org/wiki/Family_%28biology%29) [Fabaceae](https://en.wikipedia.org/wiki/Fabaceae) (or Leguminosae), commonly known as the legume, bean, or pea family. Its pod shells have various functional and bioactive properties allowing them to be used as fertilizer, food, briquettes, biofilters and part of ruminant feedstock (Udeh 2018, Maruthi *et al.,* 2019). However, when an excess of these metals accumulates in these pods, there are tendencies for it to pose health challenges to animals that use it as a component of their feedstock. Therefore, it is on this premise, that this study was carried out to determine the effect of biochar on heavy metal accumulation in the seed and pods of groundnut cultivated in heavy metal-contaminated soils.

**Materials and methods.**

**Description of the Study Location.**

The soil samples were collected from farmlands around the mining sites located in Amagu, Enyigba in Abakaliki local government area of Ebonyi State. The area (Amagu) is located between latitude 06º10’ to 06º13’ N and longitude 08º05’ to 08º10’ E in the derived savanna vegetation of the southeast ecological zone. The soil belongs to the order Ultisol, with shale as the underlying parent material (Nwaogu and Ebeniro, 2009). Mining of minerals, stone quarrying, and subsistence farming constitute the major economic activities of the people in the study area.

**Description of the Screenhouse Experimental Site.**

The study was conducted in the screen house of Soil Science and Land Resources Management Department (M.O.U.A.U). Umudike is located between the latitude 05º2’ North and longitude 07º33’ East, with an elevation of 112 m above sea level. The climate of the area is essentially humid; it has an average rainfall distribution of 2117 mm which is distributed over 10 months in a bimodal rainfall pattern. It has a relative humidity ranging from 75-76% and a temperature range of 19-35℃ (NRCRI, 2019).

**Initial Soil Sample Collection.**

The soil samples included in the tests were randomly collected at a 0-20 cm depth using a soil auger and spade. Soil samples were collected from regularly cultivated croplands adjoining the mining site. Soil samples were randomly collected from various locations, combined, air-dried at room temperature (27℃), crushed, and sieved using 4 mm and 2 mm mesh sieves for screen house and routine soil analysis following standard laboratory procedures.

**Collection of Research Materials and Production of Biochar.**

The biochar produced was derived from empty maize cob (EMCB) and subjected to pyrolysis at 400℃ within a double-barrel metallic drum (height 67 inches × diameter 22.5 inches). The pyrolytic process was conducted over a duration of 45 minutes, with the temperature measured by deploying an infrared meter. The biochar produced was allowed to cool, then thoroughly ground using an automated grinding machine to enhance its surface area, and subsequently passed through a 0.25 mm mesh sieve.

**Screenhouse Experiment.**

10kg of air-dried soil was crushed, sieved and put into 12-liter buckets. The empty maize cob biochar (EMCB) was applied at 0 t/ha-1, 20 t/ha-1, 40 t/ha-1, 60 t/ha-1, and 80 t/ha-1 which is equivalent to 0g, 88.8g, 177.6g, 266.4 and 355.2g respectively and was thoroughly mixed with the weighed soil. Water was regularly applied to moisten the soil and allowed for 3 weeks before planting to facilitate the mineralization of nutrients. The experiment was a completely randomized design (CRD) and replicated four times. Groundnut seeds were planted two weeks after biochar and water application of biochar. After 13 weeks after planting (WAP), the experiment was terminated.

**Soil Sampling and Laboratory Analyses.**

Bulk soil samples collected were subjected to soil physical and chemical analyses. Particle size was determined using Bouyoucos hydrometer method as described by Kettler *et al.,* (2001). Soil pH was determined in a 1:2:5 ratio, soil to water suspension using an electrode pH meter (Mclean, 1965). Organic carbon was determined according to Wet dichromate oxidation method as described by Walkey and Black (1934) and modified by Nelson and Sommers (1996). Available phosphorus was determined using Bray 2 method of Bray and Kurtz (1945) as described by Kuo (1996). Total nitrogen was determined using the micro kjeldhal method described by Bremner (1996). Exchangeable calcium, magnesium, sodium and potassium were extracted with NH4OAc. Calcium and magnesium were determined using Ethylene-diamine Tetra Acetic (EDTA) titration method while potassium and sodium were read using a flame photometer (Rhoades, 1982). The Aqua Regia method (3:1 ratio of HCl: HNO3) as described by Ehi-Eromosele et al., (2012) determined total heavy metals levels in both soil and plant samples. All plant samples were carefully harvested and oven-dried at a temperature of 70℃ for 72 hours until a constant weight was recorded.

**Bioaccumulation indices of Heavy Metals in Plant.**

Soil-to-plant transfer factor is an important component of human exposure to metals through the food chain, and it may reveal heavy metal bioavailability in studied soils (Rai *et al*., 2019). Selected indices include:

**Bioconcentration Factor** **(BCF).**

A plant’s ability to accumulate metals from the soil can be estimated using the BCF. The BCF was calculated using the following equation (Zheng *et al*., 2020):

BCF = Cp/Cs

Where: Cp is the metal concentration present in the plant part and Cs is the concentration of metal in soil.

**Bioaccumulation Factor (BAF).**

The BAF is an important index for understanding the potential of plants to accumulate heavy metals from soil into their edible parts. This can be calculated thus:

BAF = Cseed/Csoil

Where: Heavy metal concentrations in the edible parts of the plants and the soils are represented by Cseed and Csoil, respectively.

**Statistical Analyses.**

The data collected were subjected to analysis of variance (ANOVA) for complete randomized design using the software GenStat Discovery Edition 4 and means were separated by the least significant difference (LSD) at *p* < 0.05.

**Results and Discussion.**

**Initial soil and empty maize cob biochar (EMCB) characteristics.**

The soil physical and chemical properties used for study and the chemical properties of the empty maize cob biochar used presented is shown in Table 1. The textural class is sandy clay loam (SCL), with available phosphorus and total nitrogen content of the soil, 5.39%, and 0.074% respectively. The organic carbon, exchangeable Ca2+ and exchangeable Mg2+ content of the soil was 1.25%, 5.18%, and 1.76 cmol/kg-1 respectively. The exchangeable potassium (K) of 0.152 cmol/kg-1 and exchangeable sodium (Na) of 0.11 cmol/kg-1indicated low values according to the rating of Landon (1991). Organic carbon and total nitrogen were low while available phosphorus was moderate according to the rating of Akinrinde and Obigbesan (2000). Also, the exchangeable bases were low. Similar findings were made by Chukwu *et al*, (2013) who noted that the acidic nature and poor nutrient status of the soil could be attributed, to factors such as high rainfall can enhance the leaching of bases from the soil, further contributing to natural acidification over time. The removal of vegetation for timber, agriculture, and mining activities results in the loss of organic matter and the nutrient uptake capacity of plants, increasing the vulnerability of soil to acidification. A similar finding was also recorded by Vogel and Conedera, (2020) stating that, removal of vegetation can expose soils to accelerated leaching and erosion, propelling the acidification cycle (Vogel and Conedera, 2020).

|  |
| --- |
| **Table 1: Physical and chemical properties of the soil and biochar used in the Study** |
| **Parameters** | **Soil** | **Parameters** | **EMCB** |
| Textural Class |  SCL | **-** | **-** |
| Sand (%) | 66.0 | **-** | **-** |
| Silt (%) | 23.0 | **-** | **-** |
| Clay (%) | 11.0 | **-** | **-** |
| pH (H2O) | 4.97 | pH | 10.7 |
| Available Phosphorous (%) | 5.39 | Total Phosphorous (%) | 0.56 |
| Total Nitrogen (%) | 0.07 | Total Nitrogen (%) | 1.22 |
| Organic Carbon (%)  | 1.25 | Organic Carbon (%) | 9.74 |
| Organic Matter (%) | - | Organic Matter (%) | 16.79 |
| Exch. Calcium (cmol/kg-1) | 5.18 | Total Calcium (%) | 4.19 |
| Exch. Magnesium (cmol/kg-1) | 1.76 | Total Magnesium (%) | 1.68 |
| Exch. Potassium (cmol/kg-1) | 0.15 | Total Potassium (%)  | 2.14 |
| Exch. Sodium (cmol/kg-1) | 0.11 | Total Sodium (%) | 0.92 |
| Exch. Acidity (cmol/kg-1) | 0.82 | **-** | **-** |
|  |  |  |  |
|  |  |  |  |
| **EMCB - Empty maize cob biochar; SCL = Sandy clay loam; Exch. = Exchangeable** |

**Effects of EMCB on Zn (mg/kg) bioaccumulation in groundnut plant**.

The higher concentration of heavy metals imposes negative impacts on crops as a result of higher mobility, bioaccumulation behaviour and toxicity (Senevitatne *et al.,* 2019). The application of EMCB to the soil at 40 t/ha-1, 60 t/ha and 80 t/ha resulted in a significant increase in the amount of zinc in the soil when compared with control as shown in Table 2. At application of 80 t/ha-1 of EMCB, the soil recorded the highest zinc amount in the soil (1750 mg/kg). This may be attributed to the fact that biochar fixed the heavy metal by forming surface complexes which in turn reduced the heavy metal availability and toxic impact on the plant (Xu *et al.,* 2017). The presence of functional groups like COOH and OH in the biochar may have enabled the binding site for heavy metals to form complexes in the soil (Tan *et al.,* 2017). Similarly, the presence of organic carbon in biochar may have been responsible for the reduction in the availability and mobility of heavy metals in the soil (Zhu *et al.,* 2016) and consequently its availability to plants. The labile form of the heavy metal is converted into less mobile forms of binding with organic carbon present in the biochar (Abdelhafez *et al.,* 2014). However, the value obtained was higher than the World Health Organization (WHO) permissible limit for Zn in agricultural soils. A similar trend was also recorded in the amount of zinc observed in the shoot of the groundnut plant, empty pod and nut. Roots are the first plant organ that comes in contact with heavy metals and these heavy metals significantly reduce the root growth, root area and increased dieback which reduces the water and nutrient uptake resulting in a significant reduction in plant growth (Rucinska-Sobkowiak, 2016). The cell walls located in the roots end up becoming tough with exposure to these heavy metals which invariable inhibit plant growth (Zhao *et al.,* 2010). This plant cell membrane prevents the entry of unwanted materials into the plant organelles. This disturbs the membrane integrity and increases the loss of important solutes on exposure to heavy metal stress (Janicka-Russak *et al.,* 2012). The bioaccumulation of zinc in groundnut was observed to increase as the rates of empty maize cob biochar increased, thus following an increasing order at groundnut shoot > pod >seed > soil. The amount of Zn in the plant shoot was also observed to significantly increase (*P<0.01*) as the rates of biochar increased. At 40 t/ha-1 and 60 t/ha-1 of biochar application, the amount in the shoot exceeded the amount in the soil. This could be linked to the high mobility of zinc in the soil and also assisted by pH increase by the rate of biochar applied. The soil pH has been shown as the major factor that influences Zn distribution and speciation in soil because it affects Zn solubility and sorption in the soil solution (Adamczyk-Szabela *et al*., 2015). Usually, Zn is more bioavailable at an acid pH than at an alkaline pH Pinto *et al*., 2014]. Leitenmaier and Küpper (2013), also demonstrated that an increase in Zn’s bioavailability at a high pH can be explained by a decrease in the intra- and intermolecular hydrogen bonds in humic acid molecules.

It was also observed that the zinc values were also higher than the permissible limit of 99.4 g/g as recommended by WHO for agricultural soils. The need to analyze the concentration of zinc in the pod was due to the fact these pods are usually used as feedstock for farm animals (pigs and ruminants) as a source of fiber and protein, thereby increasing the zinc concentration along the food chain, especially when been consumed by humans.

**Table 2: Effects of EMCB on Zn (mg/kg) bioaccumulation in groundnut plant.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Biochar rates (t/ha) | Zn (Soil) | Zn (Shoot) | Zn (pod) | Zn (Seed) |
| 0 | 167 | 67 | 102 | 283 |
| 20 | 167 | 129 | 450 | 669 |
| 40 | 417 | 660 | 717 | 993 |
| 60 | 667 | 747 | 1017 | 1365 |
| 80 | 1750 | 1133 | 1483 | 1586 |
| LSD0.05 | 366.9\*\*\* | 368.0\*\*\* | 521.1\*\*\* | 545.4\*\*\* |
| WHO Permissible Limit | 50 mg/kg  | 99.41g/g |  |  |

The bioconcentration factor (BCF), bioaccumulation factor (BAF), and translocation factor (TF) were used in this study to calculate metal uptake and distribution in various plant parts. According to Table 3, the BCF values were observed between 2.4 and 7.5. Application of biochar at 2- t/ha recorded the highest (7.5) BCF value, while the highest rate of biochar application (80 t/ha) recorded the least (2.4) BCF value. The BCF value is a ratio of the metal content in different parts of the plant to that in the soil. A BCF value of greater than 1.00 suggests that the plant can accumulate metals, whereas a BCF value of ≤1.00 implies that the plant can only absorb heavy metals (Yan *et al*., 2020). In other words, a BCF value of greater than 1.00 means that the plant can take up more metals than what is available in the soil, indicating that it can hyperaccumulate heavy metals. However, a BCF value of ≤1.00 indicates that the plant cannot hyper-accumulate metals, but only absorb them in proportion to their availability in the soil. This infers that the groundnut plant is an efficient hyperaccumulator for zinc minerals in polluted agricultural soils. Bioaccumulation factor (BAF) is the ratio of metal concentration in plant tissues to that in the roots. According to the records in Table 3, the BAF values ranged between 0.9 at 80 t/ha to 4.0 at 20 t/ha biochar application. The BAF is an important index for understanding the potential of plants to accumulate heavy metals from soil into their edible parts. This index reflects the extent of metal bioaccumulation in plants relative to their concentration in soil, which can be useful for assessing the safety of consuming food crops grown in contaminated soil. A high BAF value indicates that the plant has a strong capacity for metal accumulation, which may pose risks to human health when consumed (Radovanovic *et al*., 2020).

 **Table 3: Bioaccumulation indices of Zn in groundnut cultivated.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Biochar rates** | **BCF**  | **BAF**  | **Translocation factor**  | **Translocation factor** |
| **(t/ha)** |  |  | **(seed/shoot)** | **(pod/shoot)** |
| **0** | 2.7 | 1.7 | 4.2 | 1.52 |
| **20** | 7.5 | 4.0 | 5.2 | 3.49 |
| **40** | 5.7 | 2.4 | 1.5 | 1.09 |
| **60** | 4.7 | 2.0 | 1.8 | 1.34 |
| **80** | 2.4 | 0.9 | 1.4 | 1.31 |

 Note: BCF = Bioconcentration factor; BAF = Bioaccumulation factor

Conversely, a low BAF value implies that the plant is less efficient in accumulating metals, indicating a lower risk of metal contamination in food crops. These results showed that the soil was polluted by Zn ores. Moreover, Zn concentrations in groundnut seed grains surpassed the threshold values. This observation could be attributed to the natural deposits of natural zinc ores such as zinc sulfide and marmatite. TF is the ratio of metal concentration in the aboveground plant parts to that of the root. These factors are useful for assessing the ability of plants to take up and accumulate metals from contaminated soils, and to translocate metals to the edible parts of the plants. Analyzing these factors can lead to a better understanding of the risks associated with consumingcrops grown on contaminated soils. The TF values of 1.09 – 3.49 (≥1) observed that groundnuts can hyper-accumulate zinc from shoot to pod and shoot to seed, according to Alkorta *et al*, 2004. Results from this experiment however, showed high BCF and TF values. This means that *Arachis hypogea* (groundnut) can store Zn in the shoot, pods and seed; this indicates that it is a potential phytoremediator. Therefore, could be used for phytoremediation of Zn in such an environment.

**Treatment effects of EMCB on Fe distribution in groundnut plant.**

The effect of EMCB (Empty maize cob) biochar on Fe distribution in groundnut plants is presented in Table 4. The results reviewed that Fe content in soil ranged from 2209mg/kg to 6887mg/kg. At 0 t/ha-1, the total Fe content in soil was 6887mg/kg, at 20 t/ha, Fe content was 2303mg/kg, at 40 t/ha, Fe content was 4837, at 60 t/ha, Fe content was 2770. The high values of Fe could have been responsible for the characteristic red coloration observed in the soil. However, the concentrations of Fe recorded were generally higher than the WHO permissible limit for Fe in the soil. The result on Fe content in the shoot revealed that Fe content ranged from 2219mg/kg to 3165mg/kg across the different rates of biochar. Fe content pod result revealed that Fe content ranged from 1601mg/kg to 5668mg/kg. At 0 t/ha, the Fe content in the pod was observed to be 4753mg/k, at 20 t/ha, the Fe content was observed to be 4185mg/kg, at 40 t/ha, the Fe content was observed to be 3968mg/kg, at 60 t/ha. The result also showed that Fe content was recorded to be 1601mg/kg in pod at 60t/ha-1which was the least while at 80 t/ha, the Fe content was observed to be 5668mg/kg. The result on Fe content in seed ranged from 1705mg/kg to 11537mg/kg. At 0 t/ha, Fe content in seed was observed to be 11537mg/kg, at 20 t/ha, Fe content was recorded to be 9918mg/kg, at 40 t/ha, Fe content was recorded to be 4056mg/kg, at 60 t/ha, Fe content was observed to be 1706mg/kg while at 80 t/ha, the Fe content was observed to be 2151 mg/kg. The Fe content in seed was higher than the WHO permissible limit of 20 mg/kg (WHO, 1996). Hence, these excessive values could be as result of the identified iron ores such as magnetite, hematite, siderite, iron hydroxide, etc. observed during the process of mining. The findings of this research are in line with the findings of Lahori *et al.* (2017), who observed an increase in heavy metal contents as the quantity or rate of biochar increased. Additionally, the evaluation of potential ecological risk and prediction of Zn and Fe accumulation in soil, plants, and ruminants has public health implications, emphasizing the need to assess the impact of Zn on the entire food chain, including human and animal health (Chen et al., 2021).

**Table 4: Effect of EMCB on Fe (mg/kg) distribution in the growth groundnut.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Biochar rates (t/ha) | Fe (Soil) | Fe (Shoot) | Fe (pod) | Fe (Seed) |
| 0 | 6887 | 2219 | 4753 | 11537 |
| 20 | 2303 | 2728 | 4185 | 9918 |
| 40 | 4837 | 2327 | 3968 | 4056 |
| 60 | 2770 | 3165 | 1601 | 1706 |
| 80 | 2209 | 2887 | 5668 | 2151 |
| LSD0.05 | 2936.9 | N.S | N.S | 4121.6 |
| WHO permissible limit | 40.7mg/kg | 425.5 | --- | 20 |

**Conclusion and Recommendation.**

The study showed that the soils of Amagu, Enyigba in Abakaliki were highly deficient in some essential nutrients like phosphorus, nitrogen and exchangeable bases. There were also natural deposits of zinc and iron ores littered all over the environment due to excavation and water runoff which prompted investigation on how biochar will affect bioaccumulation and phytoextraction of these naturally deposited mineral ores in this kind of polluted agricultural soil. The groundnut cultivated was shown to be an efficient hyperaccumulator because of its ability to store significant amounts of heavy metals in various parts of the plant. Biochar was shown to be efficient in bioaccumulation of zinc in polluted soil. Based on my findings I suggest that crops for consumption should not be cultivated in this area but can be used as a biomining technique in phytoremediation. An intense biomining approach can be further applied to investigate a more suitable, environmentally friendly and economical hyperaccumulator specific to each heavy metal. The intricate interplay between soil pollution and its repercussions on human health and the environment calls for an urgent and coordinated response from researchers, policymakers, and agricultural practitioners alike.

**Conflicts of Interest:**

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

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.

3.

**References**

Abdelhafez, A. A., Li, J. and Abbas, M. H. (2014). Feasibility of biochar manufactured from organic wastes on the stabilization of heavy in a metal smelter contaminated soil. *Chemosphere*, 117:66-71. <https://doi.org/10.1016/j>.

Adamczyk-Szabela, D., Markiewicz, J. and Wolf, W. M. (2025). Heavy metal uptake by herbs. IV. Influence of soil pH on the content of heavy metals in *Valeriana officinalis* L. *Water Air Soil Pollut*, *226*, 106.

Akinrinde, E. A. and Obigbesan G. O. (2000). Evaluation of fertility status of selected soils for production in five ecological of Nigeria. *Proceeding of the 26th Annual Conference of Soil Science Society of Nigeria*, Ibadan, Oyo State. 279-288.

Anjum, K. M., Yaqub, A., Bhatti, E. M., Yameen, M., Mughal, M. S., Khan, N. and Aslam, W. (2018). Assessment of zinc and lead concentration in water and muscles of Labeo rohita collected from wild and local fish farms of Pakistan. *Indian Journal of Animal Research*, *52*(11), 1560-1564.

Arshad, M. and Siddiq, S. (2022). Biochar from different sources to control heavy metal toxicity to soil microorganisms and plant. *Nveo-Natural Volatiles and Essential Oils Journal Nveo*, 2054-2063.

Beesley, L. and Dickinson, N. (2011). Carbon and trace elements fluxes in the pore water of an urban soil following greenwaste compost, woody and biochar amendments, inoculated with earthworm Lumbricus terrestris. *Soil Biology and Biochemistry*, 43(1): 188-196.

Chasapis, C. T., Loutsidou, A. C., Spiliopoulou, C. A. and Stefanidou, M. E. (2012). Zinc human health: an update. *Archives of Toxicology,* 86(4): 521–534, [https://doi.org/10.1007/s00204-011- 0775-1](https://doi.org/10.1007/s00204-011-%200775-1).

El-Sorogy, Abdelbaset S., Al-kahtany, Khaled, Alharbi, Talal, Alarifi, Saad S., (2024). Distribution patterns, health hazards, and multivariate assessment of contamination sources of As, Pb, Ni, Zn, and Fe in agricultural soils. J. King Saud Univ. Sci. 36 (11), 103489.

Fellet, G., Marmiroli, M. and Marchiol, L. (2014). Elements uptake by metal accumulators species grown on mine tailings amended with three types of biochar. *Science of the Total Environment,* (468): 595-608.

Gonmei, G., Deb, P., Kumar, P., Sinha, D., and Halder, A. (2022). Zinc Nutrition in Banana (cv. Grand Naine) at Early Growth Stage. *International Journal of Plant & Soil Science*, *34*(22), 1648-1654.

Haiying, T., Shubin, W., Ying, L., Hassan, M.U., Ying, S., Huang, G., Hashem, M., Alamri, S. and Mostafa, Y.S. (2022). Biochar: A promising soil amendment to mitigate heavy metals toxicity in plants. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 50(3): 12778- 12778.

Helaoui, S., Boughattas, I., Mkhinini, M., El Kribi-Boukhris, S., Livet, A., Bousserhine, N. and Banni, M. (2022). Biochar improves the adaptability of Vicia faba L in cadmium contaminated soil. Soil and Sediment Contamination: *An International Journal*, 1-22.

Houssou, A.A., Jeyakumar, P., Niazi, N.K., Van Zwieten, L., Li, X., Huang, L. and Huang, Z. (2022). Biochar and soil properties limit the phytoavailability of lead and cadmium by Brassica chinensis L. in contaminated soils. *Biochar,* 4(1): 1-15.

Irfan, M., Mudassir, M., Khan, M.J., Dawar, K.M., Muhammad, D., Mian, I. A., Ali, W., Fahad, S., Saud, S., Hayat, Z., Nawaz, T., Khan, A.S., Alam, S., Ali, B., Banout, J., Ahmed, S., Mubeen, S., Danish, S., Datta, R., Elgorban, A.M. and Dewil, R. (2021). Heavy metals immobilization and maize improvement (Zea mays L.) growth amended with biochar and compost. *Scientific Reports*, 11, 18416.

Janicka-Russak M., Kabała K. and Burzyński M. (2012). Different effect of cadmium and copper on H+-ATPase activity in plasma membrane vesicles from Cucumis sativus roots. *Journal of Experimental Botany*, 63:4133-4142. <https://doi.org/10.1093/jxb/ers097>.

Kalousek, P., Holátko, J., Schreiber, P., Pluháček, T., Širůčková Lónová, K., Radziemska, M. and Brtnický, M. (2024). The effect of chelating agents on the Zn-phytoextraction potential of hemp and soil microbial activity. *Chemical and Biological Technologies in Agriculture*, *11*(1), 23.

Kasozi, G. N., Zimmerman, A. R., Nkedi-Kizza, P. and Gao, B.(2010). Catechol and humic acid sorption onto a range of laboratory-produced black carbons (biochar). *Environmental Science and Technology,* 44(16): 6189-6195.

Khan, M. A., Khan, S., Khan, A. and Alam, M. (2017). Soil contamination with cadmium, consequences and remediation using organic amendments. *Science of the Total Environment,* (601-602): 1591-1605.

Kiran, K.Y., Barkat, A., Xiao-qiang, C., Ying, F., Feng-shan, P., Lin, T. and Xiao-e, Y. (2017). Cow manure and cow manure-derived biochar application as a soil amendment for reducing cadmium availability and accumulation by Brassica chinensis L. in acidic red soil. *Journal of Integrative Agriculture,* 16(3): 725-734.

Koagouw, W., Phadmacanty, N. L. P. R., Iskandar, M. R., Hindarti, D., & Arifin, Z. (2022, May). Metals in green mussels: is there any effect on their reproduction? A preliminary study of Muara Angke, Jakarta Bay. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1027, No. 1, p. 012004). IOP Publishing.

Kong, J., Huang, F., Wei, R., Zhang, X., Zhu, G., and Guo, Q. (2024). Study on the variation mechanism of Zn isotope in polluted farmland soil. *Journal of Hazardous Materials*, *479*, 135561.

Lahori, A. F., Zhanyu, G., Zengqiang, Z., Ronghua, L., Mahar, A., Awasthi, M. K., Feng, S., Sial, T.A., Kumbhar, F., Wang, P. and Jiang, S. (2017). Use of biochar as an amendment for remediation of heavy metal-contaminated soils: Prospects and challenges. *Pedosphere,* 27(6):991-1014. DOI:[10.1016/S1002-0160(17)60490-9](http://dx.doi.org/10.1016/S1002-0160%2817%2960490-9).

Landon, J.R. (1991). Booker Tropical Soil Manual. London, England: Longman Scientific and Technical Publishers.

Leitenmaier, B. and Küpper, H. (**2013).** Compartmentation and complexation of metals in hyperaccumulator plants. *Front. Plant Sci.* , *4*, 374.

Liu, W., Li, X., Li, H. H. Sr, and Wang, Y. W. (2006). Heavy metal accumulation of edible vegetables cultivated in agricultural soil in the Suburb of Zhengzhou City, People’s Republic of China.Bulletin of Environmental. Contamination and Toxicology, 76, 163–170. doi:10.1007/s00128-006-0981-3.

Mansoor, S., Kour, N., Manhas, S., Zahid, S., Wani, O.A., Sharma, V., Wijaya, L., Alyemeni, M.N., Alsahli, A.A., El-Serehy, H.A. and Paray, B.A. (2021). Biochar as a tool for effective management of drought and heavy metal toxicity. *Chemosphere,* 271:129458.

Maruthi, V., Reddy, K. S., Pankaj, P. K., Reddy, B. S. and Reddy, B. M. K. (2019). Fortified groundnut shells as a soil amendment for improved productivity in oilseed-based cropping system of Semi-Arid Tropics (SAT) India. *International Journal of Plant Production*, 13(3): 203-215.

Mazhar, R., Ilyas, N., Arshad, M. and Khalid, A. (2020). Amelioration potential of biochar for chromium stress in wheat. *Pakistan Journal of Botany,* 52(4): 1159-1168.

Mohan, D., Sarswat, A., Ok, Y. S. and Pittman Jr, C. U. (2014). Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review. *Bioresource Technology*, 160, 191-202.

Pinto, E., Aguiar, A. A., Ferreira, I. M. (2014). Influence of soil chemistry and plant physiology in the phytoremediation of Cu, Mn, and Zn. *Crit. Rev. Plant Sci.*, *33*, 351–373.

Radovanovic, V., Djekic, I. and Zarkovic, B. (2020). Characteristics of Cadmium and Lead Accumulation and Transfer by Chenopodium Quinoa Will. *Sustainability*, *12*, 3789.

Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F. and Kim, K. H. (2019). Heavy Metals in Food Crops: Health Risks, Fate, Mechanisms, and Management. *Environ. Int.* *125*, 365–385

Rucińska-Sobkowiak, R. (2016). Water relations in plants subjected to heavy metal stresses. *Acta Physiologiae Plantarum*, 38:1-13. https://doi.org/10.1007/s11738-016-2277-5.

Salam, A.K. (2022). The potential roles of biochar in restoring heavy metal polluted tropical soils and plant growth. In book: Biochar - productive technologies, properties and application, 1-21. <http://dx.doi.org/10.5772/intechopen.105791>.

Seneviratne, M., Rajakaruna, N., Rizwan, M., Madawala, H., Ok, Y.S. and Vithange, M. (2019). Heavy metal-induced oxidative stress on seed germination and seedling development: A critical review. *Environmental Geochemistry and Health*, 41: 1813-1831.

Tan, Z., Wang, Y., Zhang, L. and Huang, Q. (2017). Study of the mechanism of remediation of Cd-contaminated soil by novel biochars. *Environmental Science and Pollution Research*, 24: 24844-24855.

Udeh, B. (2018). Bio-waste transesterification alternative for biodiesel production: A combined manipulation of lipase enzyme action and aignocellulosic fermented ethanol. *Asian Journal of Biotechnology and Bioresource Technology*, 3, 1-9.

Vogel, S., and Conedera, M. (2020). Effects of land use-induced vegetation and topography changes on soil chemistry in the Southern Alps (Ticino, Switzerland). Plant, Soil and Environment, 66, 73–80.

Walkley, A. and Black, C. A. (1934). An examination of the different method of determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*, 37(1): 29-38.

Wang, W. H., Wang, Y., Li, Z., Wei, C. Z., Zhao, J. C. and Sun, L. G. (2018). Effect of a strengthened ecological floating bed on the purification of urban landscape water supplied with reclaimed water: *Science of the Total Environment,* (622-623), 1630–1639. doi:10.1016/j.scitotenv.2017.10.035.

World Health Organization, (1996). Chromium in drinking water. Background document for development of WHO guidelines for drinking water quality. *Geneva, Switzerland,* WHO/SDE/WSH/03.04/04.

Xu, X., Zhao, Y., Sima, J., Zhao, L., Mašek, O. and Cao, X. (2017). Indispensable role of biochar-inherent mineral constituents in its applications: A review. *Bioresource Technology*, 241: 887-899. <https://doi.org/10.1016/j.biortech.2017.06.023>.

Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S. and Chen, Z. (2020). Phytoremediation: A Promising Approach for Revegetation of Heavy Metal-Polluted Land. *Front. Plant Sci.* *11*, 359.

Zhao, S., Liu, Q., Qi, Y. and Duo, L. (2010). Responses of root growth and protective enzymes to copper stress in turfgrass. *Acta Biologica Cracoviensia Botanica*, 52:7-11.

Zheng, S., Wang, Q., Yu, H., Huang, X., Li, F. (2020) Interactive Effects of Multiple Heavy Metal(Loid)s on Their Bioavailability in Cocontaminated Paddy Soils in a Large Region. *Sci. Total Environ.* *708*, 135126.

Zhu, H., Zhong, H. and Wu, J. (2016). Incorporating rice residues into paddy soils affects methylmercury accumulation in rice. *Chemosphere,* 152: 259-264. <https://doi.org/10.1016/j.chemosphere.2016.02.095>.