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Mitigation Strategies for Reducing Heavy Metal Content by Application of Biochar

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Abstract
Heavy metal contamination in soil is a major problem worldwide, causing harm to plants, animals, and human health. These metals come from various sources like industrial waste, mining, and improper use of chemicals in agriculture. Reducing heavy metals in soil is challenging, but biochar offers a promising and sustainable solution. Biochar is a charcoal-like material made from plant or animal waste through a process called pyrolysis, where the material is burned without much oxygen. It has unique properties, such as a high surface area and the ability to improve soil quality. Biochar can help trap heavy metals in soil, making them less harmful to plants and reducing their movement into groundwater or crops. This paper explores how biochar works to reduce heavy metals in soil. It discusses the physical, chemical, and biological ways biochar interacts with metals. Factors like the type of material used to make biochar, how it is produced, and soil properties play a big role in its effectiveness. For example, biochar can change soil pH, increase nutrient availability, and support beneficial microbes, which all help in heavy metal reduction. The paper also reviews successful cases where biochar reduced metals like lead (Pb), cadmium (Cd), and arsenic (As) in contaminated soils. While biochar shows great potential, challenges such as cost, large-scale application, and variability in results need to be addressed.
Keywords: Biochar, Heavy Metals, Arsenic, Plants Growth, Lead

Introduction

Heavy metal contamination in soil is a significant global issue that affects both the environment and human health (Zaib et al., 2023a; Bayar et al., 2024; Zeeshan et al 2024a). Heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) often enter the soil through industrial waste, mining activities, and the excessive use of chemical fertilizers and pesticides (Zaib et al., 2023b; Ge et al., 2024; Zeeshan et al., 2023a). These metals can harm plant growth, reduce crop yields, and enter the food chain, posing risks to both animals and humans (Zaib et al., 2023c; Zubair et al., 2023a; Zeeshan et al 2023b). Although various methods exist for removing heavy metals, such as chemical treatments and soil washing, these approaches can be costly and may have adverse environmental effects, highlighting the need for safer and more affordable solutions (Zaib et al., 2023d; Zubair et al., 2023b; Zeeshan et al 2024b). Heavy metals in soil can significantly impact its biological and chemical properties (Zaib et al., 2023e; Abbas et al., 2023a; Zeeshan et al 2023c). For instance, the metabolic quotient (qCO_2) serves as an indicator of how heavy metal pollution adversely affects soil microorganisms (Zaib et al., 2023f; Abbas et al., 2023b; Zeeshan et al 2023d). Research indicates that even when the basic respiration activity in contaminated soils remains relatively stable, the metabolic quotient can be twice as high in these soils compared to uncontaminated ones (Zaib et al., 2023g; Afzal et al., 2023a; Zeeshan et al 2023e). This suggests that heavy metals can decrease the number of microorganisms in the soil (Zaib et al., 2023h; Afzal et al., 2023b; Zeeshan et al 2024c), which are essential for maintaining healthy soil ecosystems (Zaib et al., 2023i; Raza et al., 2023; Zeeshan et al 2023f). The sources of heavy metal pollution are diverse and include activities such as mining, smelting, and the use of agrochemicals (Zaib et al., 2023j; Aslam et al., 2024; Zeeshan et al 2024d). These activities lead to the accumulation of heavy metals in the soil, which can have long-lasting environmental effects. Industries such as chemical manufacturing, textiles, and cement production are known to contribute significantly to heavy metal contamination in soils (Zaib et al., 2023k; Iftikhar et al., 2023; Zeeshan et al 2023g). This widespread issue necessitates urgent attention and effective remediation strategies to safeguard both the environment and public health (Zaib et al., 2023l; Ali et al., 2023). One promising approach to remediating contaminated soils is bioremediation. This method enhances natural processes that break down pollutants, allowing plants to absorb and remove heavy metals from the soil. Techniques such as phytoremediation, where plants are utilized to extract metals, and rhizofiltration, where plant roots filter out contaminants, exemplify how bioremediation can be applied. The effectiveness of these methods depends on various factors, including the type of heavy metal present, the growing season, and the plants' capacity to accumulate metals (Zaib et al., 2023m; Zeeshan et al 2024e). In addition to bioremediation, other methods for treating contaminated soils have been explored (Zaib et al., 2023n; Zaib, 2024a). For example, some studies have investigated new washing agents that can effectively remove heavy metals from polluted soils. These agents can also assist in treating wastewater generated during the washing process, enhancing the overall efficiency and environmental friendliness of remediation efforts. However, the challenge remains to identify solutions that are both effective and do not cause further environmental harm (Zaib et al., 2023o; Zaib, 2024b). Overall, heavy metal contamination in soil is a complex issue that requires a multifaceted approach for resolution. While traditional remediation methods exist, there is a growing need for innovative and sustainable solutions that can effectively eliminate heavy metals without causing additional environmental damage. Research into bioremediation and the development of new washing agents are promising areas that could lead to safer and more cost-effective methods for cleaning contaminated soils (Zaib et al., 2023p; Zaib and Adnan, 2024).

Research has shown that the effectiveness of biochar in immobilizing heavy metals depends on several factors, including the type of metal, the biomass source used to create the biochar, and the pyrolysis conditions (Zaib et al., 2023q; Zaib et al., 2024). For instance, studies indicate that different types of biochar can have varying impacts on soil health and metal immobilization, highlighting the importance of selecting appropriate feedstock and pyrolysis conditions to produce high-quality biochar. Furthermore, the presence of harmful compounds such as polycyclic aromatic hydrocarbons (PAHs) in biochar can adversely affect plant growth, which is a critical consideration when using biochar in agricultural settings. The pH level of the soil can also change upon the addition of biochar, which can be beneficial for acidic soils. Research indicates that biochar can act as a liming agent, helping to increase soil pH and improve overall soil quality. This is particularly advantageous in regions with naturally acidic soils, as it can create a more favorable environment for plant growth. Additionally, biochar can enhance nutrient retention in the soil, which is essential for healthy plant development (Zaib et al., 2023r).

Biochar is a promising method for addressing heavy metal pollution in soil. It is a type of charcoal produced by heating organic materials, such as crop residues, wood, or animal waste, in a low-oxygen environment, a process known as pyrolysis. Biochar possesses unique characteristics, including a large surface area and a porous structure, which can enhance soil quality. When incorporated into contaminated soil, biochar can immobilize heavy metals, reducing their bioavailability to plants and preventing their leaching into water sources. Additionally, biochar can improve soil fertility by enhancing nutrient retention and supporting beneficial microorganisms, making it an environmentally friendly option. This paper will explore how biochar can reduce heavy metal concentrations in polluted soils. It will examine the physical, chemical, and biological interactions between biochar and heavy metals and identify factors that influence its effectiveness, such as the type of biomass used to produce biochar and the conditions during pyrolysis. Furthermore, this research will review successful case studies and recommend best practices for biochar application in real-world scenarios. By understanding the mechanisms of biochar, we can advocate for its use as a sustainable and cost-effective tool for managing heavy metal pollution and promoting soil health (Zaib et al., 2023s).

Materials and Methods

Crop Selection

Maize (Zea mays L.) was chosen for this study due to its widespread cultivation in Pakistan and its sensitivity to heavy metal stress, making it an ideal indicator crop for evaluating soil amendments.

Research Plan

This research was conducted in the wirehouse of the College of Agriculture, University of Sargodha, Punjab, Pakistan. Soil and organic amendments were collected from the Soil Science Laboratory, and all analyses were performed in the Soil Science High-Tech Laboratory. The research methodology included the following steps:

Experimental Setup:

- A randomized complete block design (RCBD) with three replicates was used.
- Treatments included a control (untreated soil) and soils amended with biochar, poultry manure, farmyard manure, and compost.

Soil Sampling and Preparation:

- Soil was collected from a lead (Pb)-contaminated site, air-dried, and sieved (2 mm).
- Baseline soil characteristics, including pH, electrical conductivity (EC), organic matter, and lead content, were analyzed.

Biochar and Organic Amendments:

- Biochar was prepared using wheat straw at 450°C.
- Poultry manure, farmyard manure, and compost were sourced and characterized for nutrient content (N, P, K) and heavy metal levels.

Plant Growth Experiment:

- Maize seeds were sown in pots containing 5 kg of soil per treatment.
- Amendments were applied at 2% w/w to the soil before sowing.

Data Collection:

Physiological Parameters: Plant height, leaf area, chlorophyll content (SPAD readings), and biomass yield were recorded.

Chemical Parameters: Soil pH, EC, organic matter, available Pb, and nutrient content (N, P, K) were analyzed.

Biological Parameters: Soil microbial activity (dehydrogenase activity) and microbial biomass carbon (MBC) were measured.

Statistical Analysis:

Data were analyzed using ANOVA, and treatment means were compared using the LSD test at

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a 5% significance level.
Table 1: Physiological Parameters of Maize

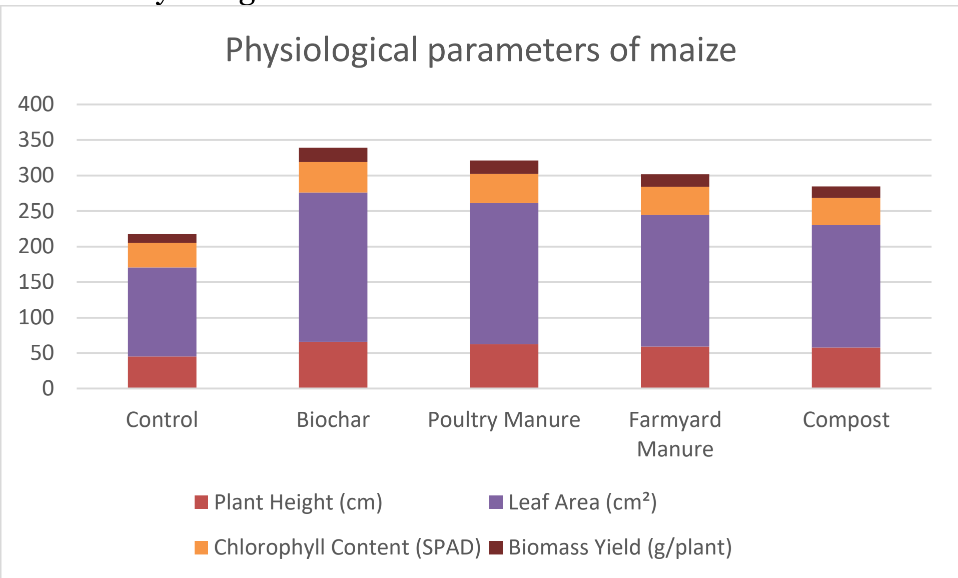

Table 2: Chemical Parameters of Soil

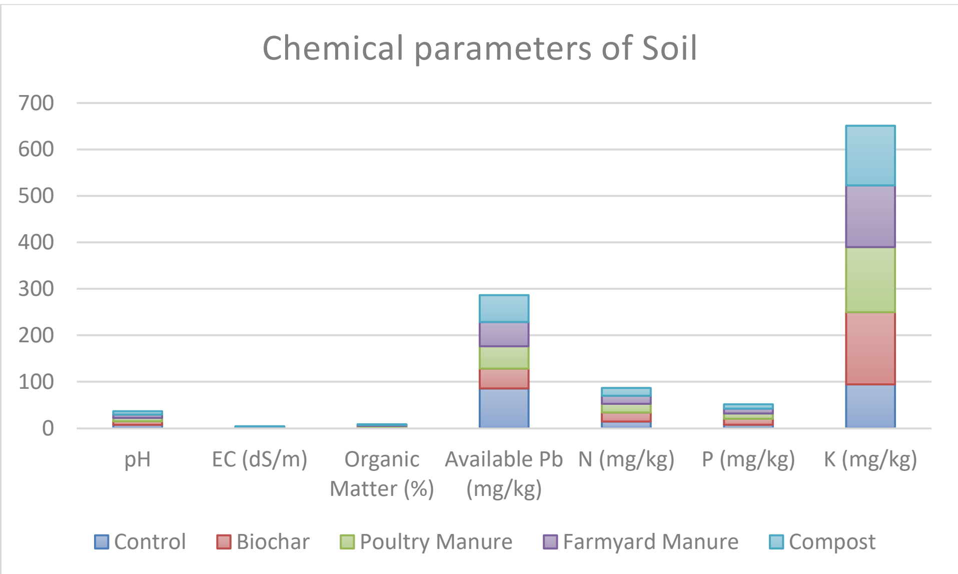

Table 3: Biological Parameters of Soil

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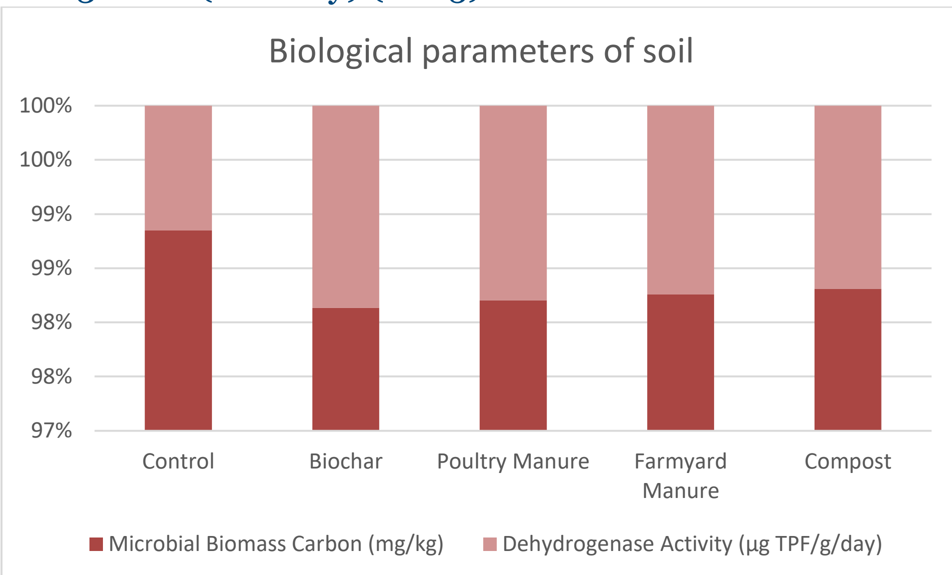

Results and Discussion

Physiological Parameters

The results showed that soil amendments significantly improved maize growth. Among the treatments, biochar led to the highest plant height (65.8 cm), leaf area (210.3 cm^2), chlorophyll content (42.7 SPAD), and biomass yield (20.6 g/plant). Poultry manure also showed notable improvements, but the effects were slightly lower than biochar. The control group exhibited the least growth performance, indicating the adverse impact of lead contamination on maize. These findings suggest that biochar is highly effective in mitigating lead stress and promoting plant growth due to its ability to immobilize heavy metals and improve soil structure.

Chemical Parameters

Soil chemical properties varied significantly among treatments. Biochar increased soil pH from 7.1 (control) to 7.5, reducing lead availability from 85.4 mg/kg to 42.6 mg/kg. This reduction in lead availability is attributed to biochar's high adsorption capacity and ability to form stable complexes with heavy metals. Organic matter content also increased with all amendments, with biochar achieving the highest improvement (2.15%). Poultry manure and compost enhanced nitrogen, phosphorus, and potassium availability, but biochar outperformed them in enhancing overall soil nutrient content. These results confirm the dual role of biochar in reducing heavy metal toxicity and enhancing soil fertility.

Biological Parameters

The biological analysis revealed that soil microbial activity and microbial biomass carbon (MBC) were highest in the biochar-amended soil, recording 5.8 µg TPF/g/day and 305 mg/kg, respectively. Poultry manure and farmyard manure also boosted microbial activity, but their impact was less pronounced. The control treatment showed the lowest microbial activity and MBC, indicating that heavy metal stress negatively impacts soil microbial health. The improved biological parameters with biochar are likely due to its ability to create a favorable microenvironment for microbial growth by reducing heavy metal toxicity and improving soil aeration and water-holding capacity.

Conclusion

In conclusion, biochar presents a sustainable and effective strategy for mitigating heavy metal contamination in soils. Its unique properties, such as high surface area, porous structure, and ability to alter soil pH and support microbial activity, make it an excellent amendment for immobilizing heavy metals like lead, cadmium, and arsenic. This review highlights how biochar reduces heavy metal bioavailability, enhances soil fertility, and promotes plant growth, making it a valuable tool for environmental remediation. However, factors such as biochar production methods, feedstock type, and soil conditions must be carefully considered to optimize its effectiveness. Future research should focus on addressing challenges related to cost, large-scale application, and variability in results to fully realize the potential of biochar in managing heavy metal contamination.

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