

# Predicting Biochar-Mediated Cadmium Immobilization in Agricultural Soils Using Explainable Machine Learning: A Circular Approach to Food Safety

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Sustainable solid waste management increasingly promotes the valorization of organic residues into functional materials capable of addressing environmental challenges. Among these strategies, biochar derived from organic waste streams has emerged as a promising soil amendment for heavy metal immobilization and risk mitigation in agricultural systems. However, predicting the effectiveness of biochar in reducing metal bioavailability and plant uptake remains complex due to strong interactions between soil physicochemical properties, amendment characteristics, and plant dynamics (Serrano et al., 2023).

This study evaluates the potential of waste-derived biochar to reduce cadmium (Cd) bioavailability in agricultural soils cultivated with common bean (*Phaseolus vulgaris*), aiming to improve food safety while advancing circular resource management. Soil physicochemical parameters (pH, electrical conductivity, cation exchange capacity, total carbon and nitrogen) were monitored alongside soil Cd bioavailability and plant Cd uptake. To enhance predictive capacity and support decision-making in amendment application, we developed an explainable machine learning (ML) framework capable of estimating Cd bioavailability and plant Cd concentrations under biochar-amended and non-amended scenarios.

Tree-based regression algorithms were trained using grouped cross-validation to ensure robust prediction across experimental replicates. Model interpretability was assessed using SHAP analysis to quantify the relative contribution of soil properties and biochar addition to Cd immobilization and plant uptake reduction. This approach enables identification of the dominant soil drivers controlling Cd dynamics and quantifies the marginal effect of biochar application under varying soil conditions.

The integration of waste-derived biochar with explainable artificial intelligence offers a data-driven framework to optimize amendment strategies, reduce heavy metal risks in food crops, and promote circular economy principles in agricultural soil management. By transforming organic waste into a functional remediation amendment and coupling it with predictive analytics, this study contributes to sustainable solid waste valorization pathways that simultaneously address soil health, food safety, and environmental protection.

## References

- Serrano, M. F., López, J. E., Henao, N., & Saldarriaga, J. F. (2023). Phosphorus-Loaded Biochar-Assisted Phytoremediation to Immobilize Cadmium, Chromium, and Lead in Soils. *ACS Omega*.  
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