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Quantifying PFAS Immobilization in Biochar-Amended Soils: Rapid Small-Scale Column Tests Coupled with Uncertainty-Aware Reactive Transport Modeling

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Per- and polyfluoroalkyl substances (PFAS) are increasingly detected in soils and groundwater, challenging conventional remediation strategies due to their persistence and mobility. Steam-activated biochars (SA-BCs), produced from renewable agricultural residues, are emerging as lower-footprint alternatives to conventional activated carbons for PFAS sorption. However, quantitative assessments under field-relevant flow-through conditions, and the robustness of derived transport parameters, remain limited. Here, we combine small-scale column experiments with uncertainty-integrated reactive transport modeling to evaluate PFAS immobilization in biochar-amended soils.

We investigated the sorption of seven C4–C8 per- and polyfluoroalkyl acids in synthetic groundwater using 4 cm × 1 cm flow-through columns packed with loamy sand amended with 0.5% SA-BC. Breakthrough curves were analyzed using the Ogata–Banks analytical solution to the one-dimensional advection–dispersion equation. To explicitly quantify the impact of experimental variability, a Monte Carlo framework was implemented to propagate uncertainties in flow rate, porosity, and measured PFAS concentrations into fitted retardation factors.

In untreated soil blanks, most compounds exhibited immediate breakthrough, confirming negligible intrinsic retention. In contrast, amendment with 0.5% SA-BC resulted in pronounced retardation, with retardation factors ranging from ~10 for PFBA to ~1600 for PFOS. Elution order followed chain length and functional group, consistent with increasing hydrophobicity and sorption affinity. For PFOS, Monte Carlo simulations assuming relative uncertainties of 5% in flow rate, porosity, and concentration yielded R = 1556 ± 333 (1 SD), demonstrating that even moderate experimental variability can substantially affect fitted transport parameters.

These results demonstrate that low-dose SA-BC amendment can markedly reduce PFAS mobility under advective conditions representative of subsurface flow. At the same time, they show that uncertainty propagation is essential for deriving reliable retardation factors and for translating laboratory column data to field-scale predictions. Ongoing work addresses the influence of matrix composition and geochemical variability on reactive transport. Together, this approach establishes a mechanistically grounded, uncertainty-aware framework for evaluating biochar-based in situ immobilization of PFAS in contaminated soils under realistic environmental conditions.

