

Integrated Chitosan–Biochar Immobilization Platform for PFAS-Impacted Soil and Water Remediation

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The remediation of per- and polyfluoroalkyl substances (PFAS) requires robust, multi-stage intervention due to the recalcitrance, mobility, and regulatory stringency associated with these compounds. This technical white paper presents a formal protocol and rationale for an integrated remediation platform utilizing a chitosan–biochar composite. Specifically, this platform leverages chitosan oligosaccharide–hydrochloride (COS-HCl) as a highly reactive, positive-charge supplemental amendment, hybridized with high-surface-area engineered biochar.

The proposed amendment specification utilizes COS-HCl with a degree of deacetylation (DDA) of 98%, a molecular weight of 3 kDa, and a surface charge of approximately +71 mV. It is critical to state that COS-HCl is proposed herein as a *supplemental amendment*—designed to be stabilized onto a biochar matrix—rather than a standalone remedy. When integrated correctly, this platform acts as a critical component within a broader treatment train that includes source delineation, hotspot excavation, hydraulic containment, and point-of-entry guard beds.

GRANT REVIEW VALUE PROPOSITION

This integrated platform directly addresses fundamental gaps in current PFAS remediation practice:

- **Source-Mass Reduction:** Stabilizes leachable PFAS in the vadose and saturated zones, driving down long-term mass flux.
- **Lower Mass Flux:** Reduces the loading burden on downstream water-treatment systems, extending the life of costly Granular Activated Carbon (GAC) and Ion Exchange (IX) resins.
- **Renewable Feedstocks:** Utilizes naturally derived biopolymers (chitosan) and carbon-sequestering biochar, improving the sustainability and lifecycle footprint of the remedial action.
- **Pilotable Implementation:** Integrates smoothly into conventional soil mixing and pump-and-treat frameworks without requiring unproven field equipment.

2. Basis for the Integrated Remedy

According to the Interstate Technology and Regulatory Council (ITRC) [8], PFAS remedial design must adopt a tiered logic. The primary directive is the protection of drinking water and human receptors. Once points-of-exposure are secured, source control and mass-flux reduction are required to mitigate long-term liability.

Field-implemented full-scale technologies for PFAS-impacted liquids are currently dominated by sequestration strategies, specifically GAC, IX, and Reverse Osmosis (RO). However, these technologies face profound limitations. Short-chain PFAS (e.g., PFBS, PFHxA) experience rapid breakthrough in GAC systems. High concentrations of naturally occurring organic matter (NOM) or total organic carbon (TOC) prematurely foul both GAC and IX media. Furthermore, spent media require carefully controlled disposal, thermal reactivation, or incineration to prevent secondary environmental release. By implementing an upstream chitosan-biochar immobilization step, the proposed architecture curtails the mass flux entering these conventional systems.

3. Product and Amendment Rationale

Chitosan, derived from chitin, is a unique biopolymer possessing a primary positive electrostatic charge—an attribute highly favorable for binding anionic PFAS. Chitosan Global describes chitosan as a potent binder capable of integration with biochar and microbial systems for comprehensive soil and water remediation [1].

The specific material proposed for this protocol, Chitosan Oligosaccharide Hydrochloride (Mushroom-derived), is highly refined for water-treatment applications [2, 3]. According to the manufacturer's Certificate of Analysis [4], the input specifications include:

- **Purity:** 98.5%
- **Viscosity:** 1.3 cS (indicative of low molecular weight)
- **pH:** 3.40 (1% solution in distilled water)
- **Solubility:** Fully soluble in water (9.89% in DM water) with minimal insoluble matter (0.10%).

WHY COS-HCL IS SUPPLEMENTAL RATHER THAN STANDALONE

While highly pure, soluble COS-HCl provides exceptional charge density (+71 mV), excellent wetting properties, and maximum interfacial contact with PFAS anions, its inherent water solubility is a liability for in situ deployment if used alone. In a standalone application, soluble chitosan would be susceptible to rapid groundwater washout. Therefore, it must be deployed as a *supplemental amendment*. By thoroughly blending the soluble COS-HCl into an engineered biochar matrix during application, the biochar provides a high-surface-area, stable physical scaffold. The chitosan functionalizes the biochar surface, yielding a resilient composite that resists washout while actively capturing PFAS through complementary electrostatic and hydrophobic mechanisms.

4. Evidence Base from Scientific Literature (2020–Present)

The field performance expectations for this platform are derived conservatively from recent peer-reviewed studies investigating integrated chitosan-based adsorbents:

- **Modified Quaternized Chitosan Hydrogels (MQCGs) [5]:** A 2025 study demonstrated that surface-modified quaternized chitosan achieved complete removal of long-chain PFAS (PFOS, PFOA) and >99.9% removal of short-chain PFAS (PFBS, PFHxA) at 500 µg/L concentrations. Adsorption of >98% PFOS occurred in <30 minutes. The material was effective across a wide pH window (3 to 12), exhibiting a high zeta potential (+44.8 mV). Furthermore, it was regenerated for 10 cycles using a simple 0.025 M NaCl solution while maintaining ~98% efficiency. The mechanisms identified included electrostatic, hydrophobic, and physical channel interactions.
- **Chitosan-Coated Covalent Organic Frameworks (COF@CS) [6]:** A 2024 study evaluating a chitosan-coated framework recorded a maximum PFOA capacity of 2.8 mmol/g at pH 5, with a rapid adsorption rate of 6.2 mmol/g/h. The composite was successfully regenerated for 5 cycles utilizing 70% ethanol and 1 wt% NaCl. The study proved that combining quaternary amines with protonated amino groups from chitosan drives aggressive electrostatic adsorption, reinforcing the necessity of composite integration.
- **Chitosan-Modified Magnetic Biochar (CS_MBC) [7]:** A 2025 assessment of chitosan-modified biochar found an optimal 1:1 chitosan loading ratio yielded ~94% PFOA removal. While batch Langmuir capacity was extremely high (~517 mg/g), fixed-bed column experiments demonstrated a practical capacity of 39.63 mg/g. The optimal operational window was pH 4 at a 60-minute contact time. This study emphasizes the need for conservative scale-up, as dynamic column capacities are typically an order of magnitude lower than batch isotherms.

5. Proposed Remedial Architecture

The integrated remedy employs a treatment train methodology to address source zones, flux pathways, and point-of-exposure vulnerabilities.

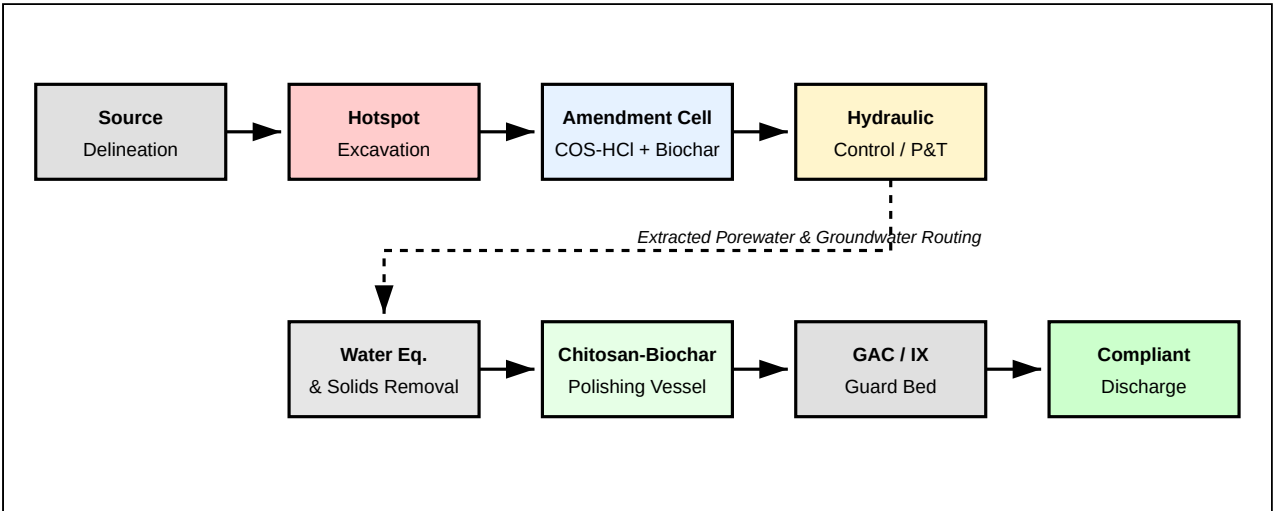


Figure 1. Remediation treatment-train architecture illustrating the integration of soil stabilization and water-polishing stages utilizing the chitosan-biochar platform alongside conventional methodologies.

Table 1. Comparison of Technology Roles within the Treatment Train

Technology	Primary Role	PFAS Action
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Technology	Primary Role	PFAS Action
Excavation	Source Zone Hotspot Removal	Physical removal of gross mass; off-site destruction/landfill.
Capping / Containment	Hydraulic Isolation	Prevents infiltration; limits leachate generation.
Chitosan-Biochar Amendment	Vadose / Saturated Zone Stabilization	In-situ immobilization reducing mass flux; binds long & short chains.
Hydraulic Control (P&T)	Plume Management	Extracts mobile mass; captures escaping flux.
Primary Treatment (e.g., RO/Foam)	Bulk Liquid Treatment	Separates/concentrates high-level aqueous PFAS.
Chitosan-Biochar Polishing	Pre-Treatment / Polishing	Mitigates organic fouling; removes residual low-level PFAS.
GAC / IX Guard Bed	Point of Compliance	Final effluent polishing to strict non-detect regulatory standards.

6. Ideal Step-by-Step Protocol for PFAS-Impacted Soil and Associated Water

The following protocol addresses both contaminated soils and the associated contact/extracted water.

6.1. Soil Matrix Protocol

- Site Preparation & Delineation:** Conduct high-resolution site characterization to define the plume architecture. Segregate soils based on decision logic: concentrations exceeding maximum threshold criteria are designated for physical excavation and thermal destruction; intermediate concentrations are designated for in-place amendment.
- Amendment Blending Sequence:** Stage the engineered biochar. Using controlled spray application, hydrate the biochar with a specifically titrated solution of COS-HCl (adjusted to the site's optimum moisture demand). Ensure intimate interfacial contact between the soluble chitosan and the carbon matrix.
- Mixing & Placement:** Employ rotary mixers, pug mills, or large-scale excavators to blend the chitosan-biochar composite into the targeted soil in controlled lift thicknesses (e.g., 1 to 2 feet).
- Curing & Containment:** Allow the amended soil to undergo a curing/contact period. Apply temporary erosion control and surface capping to manage stormwater infiltration.

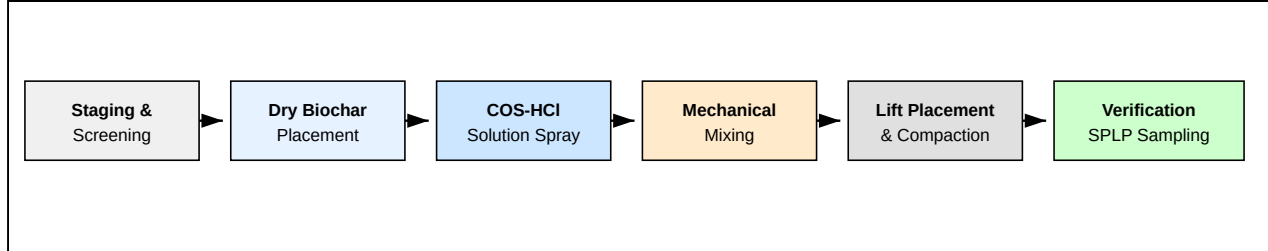


Figure 2. Soil amendment application workflow demonstrating the integration sequence of biochar and soluble COS-HCl.

6.2. Water Matrix Protocol (Porewater / Groundwater / Stormwater)

1. **Extraction & Equalization:** Route dewatering liquids, captured groundwater, and contact stormwater to an equalization tank.
2. **Solids Removal:** Pass liquid through bag filters or sand media to remove bulk suspended solids.
3. **Primary PFAS Removal:** Depending on the influent concentrations, utilize foam fractionation or equivalent bulk separation.
4. **Chitosan-Biochar Polishing:** Route the effluent through a contactor vessel loaded with a stabilized chitosan-biochar granular composite. This step acts as an organic scavenger and targets recalcitrant short-chain PFAS.
5. **Final Guard Bed:** Pass the polished water through a standard GAC or IX system to ensure absolute regulatory compliance prior to discharge or reinjection.

7. Design Basis and Preliminary Application Rates

The values presented below are conservative, proposal-ready ranges intended to serve strictly as *pilot-scale starting points*. They must be empirically refined via site-specific treatability testing.

- **Soil Amendment Blend:** Engineered biochar applied at 2% to 5% dry weight of treated soil.
- **COS-HCl Loading:** Chitosan oligosaccharide-hydrochloride applied at 0.1% to 0.5% dry weight of treated soil. Equivalently, the chitosan solids should represent roughly 1 part to 10–20 parts biochar by dry mass. Solution addition must be adjusted dynamically to the soil's optimum moisture demand.
- **Water Polishing (Empty Bed Contact Time - EBCT):** For the chitosan-biochar contactor acting as a polishing step, an EBCT target range of 10 to 30 minutes is recommended for pilot testing.

8. Monitoring, QA/QC, and Decision Criteria

Robust post-treatment verification criteria must be instituted to validate the immobilization platform:

- **Leachability Testing:** Conduct Synthetic Precipitation Leaching Procedure (SPLP) or site-appropriate leach tests (e.g., LEAF methodology) to verify the reduction of mobile PFAS fractions in amended soils.

- **Total PFAS vs. Target Analytes:** Monitor specific regulatory target analytes (PFOS, PFOA, PFHxS) while utilizing total oxidizable precursor (TOP) assays to ensure precursors are immobilized.
- **Groundwater Trends:** Monitor downgradient flux reduction through network sampling.
- **Media Breakthrough:** Continually track differential pressure and PFAS breakthrough curves across the water-side polishing and guard beds.

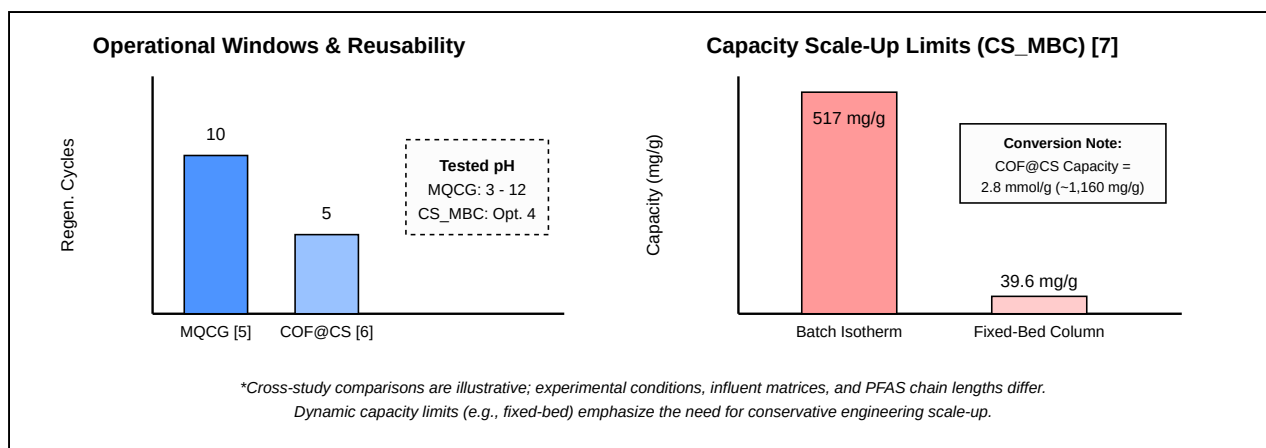


Figure 3. Extracted literature metrics demonstrating the stability (regeneration) and necessary scaling conservatism (batch vs. dynamic column capacity) associated with chitosan-modified matrices.

9. Residuals and Waste Management

All spent media and generated waste must be managed strictly following federal and state guidelines. Although the chitosan-biochar composite firmly immobilizes PFAS, spent media from the water polishing systems will eventually exhaust. Common, compliant options for spent media management include off-site thermal destruction via commercial incineration, high-temperature cement kilns, or appropriately permitted landfilling (where leachate management is heavily scrutinized) [8].

10. Limitations, Risk Controls, and Scale-Up Considerations

The proposed remedy must be engineered to account for known limitations inherent to biopolymer sorbents:

- **Capacity Drop in Dynamic Flow:** As demonstrated by Saawarn et al. [7], fixed-bed column capacities (39.63 mg/g) can be significantly lower than theoretical batch maximums (517 mg/g). Scale-up designs must utilize the conservative dynamic capacity.
- **Washout Risks:** Bonding COS-HCl onto the biochar support is mandatory for geotechnical stability.
- **Fouling and Competition:** Natural organic matter (NOM) can compete for adsorption sites on the biochar matrix, reducing the total available capacity for PFAS. The dual-mechanism (electrostatic from chitosan + hydrophobic from biochar) mitigates this risk, but pretreatment (e.g., solids removal) remains essential.

11. Conclusions

An integrated immobilization platform combining chitosan oligosaccharide-hydrochloride with engineered biochar offers a highly viable, sustainable approach to managing PFAS mass flux. By acting as a targeted amendment within a comprehensive treatment train, the positively charged chitosan effectively binds both long- and short-chain PFAS, while the biochar matrix ensures physical stability and hydraulic compatibility. When coupled with conservative scale-up practices, precise execution protocols, and conventional polishing guards, this methodology fulfills the regulatory mandate to protect downstream receptors while actively mitigating source-zone liabilities.

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