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# Reactive Soil Mixes for Enhanced PFAS Adsorption in Stormwater Infiltration Basins: Mechanisms and Field Assessment

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## ABSTRACT

Per- and polyfluoroalkyl substances PFAS have emerged as persistent contaminants of concern in urban stormwater systems due to their chemical stability, mobility, and resistance to conventional treatment processes. Stormwater infiltration basins, while effective for hydrologic control, may facilitate PFAS migration into subsurface environments if not properly engineered. This study investigates the effectiveness of reactive soil mixes incorporating biochar, zeolite, and iron oxide as amendment media for enhanced PFAS adsorption in stormwater infiltration basins. Laboratory-scale adsorption assessments were combined with field-scale demonstration and pre- and post-infiltration monitoring to evaluate retention performance and dominant adsorption mechanisms. Results indicate that blended reactive media significantly improve PFAS attenuation compared to native soils, with adsorption governed by a combination of electrostatic interactions, hydrophobic partitioning, and surface complexation. Field observations confirm sustained PFAS reduction under operational stormwater loading, supporting the integration of reactive soil amendments as a practical strategy for mitigating PFAS transport in infiltration-based stormwater management systems.

**Keywords:** PFAS adsorption, Stormwater infiltration basins, Reactive soil mixes, Biochar, Zeolite, Iron oxide.

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## INTRODUCTION

Urban stormwater management systems have undergone a significant transition from purely hydraulic control structures to multifunctional infrastructure designed to improve water quality and protect receiving environments. Stormwater infiltration basins are central to this transition, as they reduce surface runoff volumes, attenuate peak flows, and promote groundwater recharge. Despite these benefits, growing attention has been directed toward their role as potential pathways for the transport of persistent and mobile contaminants, particularly per- and polyfluoroalkyl substances PFAS, into subsurface and groundwater systems.

PFAS comprise a large class of synthetic fluorinated compounds widely used in industrial processes and consumer products due to their resistance to heat, water, and chemical degradation. These same properties contribute to their environmental persistence and widespread occurrence in urban runoff. Sources of PFAS in stormwater include atmospheric deposition, roadway runoff, building materials, firefighting foam residues, and industrial land uses. Once mobilized during rainfall events, PFAS can be conveyed into infiltration-based systems where conventional soil matrices often provide limited attenuation.

Natural soils typically exhibit low sorptive capacity for PFAS because of electrostatic repulsion between negatively charged soil surfaces and anionic PFAS functional groups, as well as the limited organic carbon content of sandy infiltration media. Short-chain PFAS are particularly problematic due to their high solubility and weak affinity for soil particles, allowing rapid migration through the vadose zone. As a result, infiltration basins designed without targeted treatment enhancements may unintentionally facilitate PFAS transport to underlying aquifers.

In response to these challenges, research efforts have increasingly focused on the incorporation of reactive media into infiltration systems to enhance contaminant retention while maintaining hydraulic performance. Reactive soil

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mixes offer a promising solution by introducing materials with tailored surface properties capable of interacting with PFAS through multiple adsorption mechanisms. Carbon-based materials such as biochar provide hydrophobic and π–π interactions, while mineral-based amendments such as zeolite and iron oxides contribute electrostatic attraction, ion exchange, and surface complexation pathways.

Although laboratory studies have demonstrated the PFAS sorption potential of individual reactive media, uncertainties remain regarding their combined performance within engineered soil matrices and under realistic field conditions. Factors such as stormwater chemistry, variable hydraulic loading, aging of sorbent materials, and competitive adsorption from co-occurring contaminants can influence long-term effectiveness. Moreover, limited field-scale evaluations have constrained the translation of laboratory findings into practical stormwater design guidance.

This study addresses these knowledge gaps by systematically evaluating reactive soil mixes containing biochar, zeolite, and iron oxide for enhanced PFAS adsorption in stormwater infiltration basins. By integrating mechanistic adsorption analysis with field-scale demonstration and pre- and post-infiltration monitoring, the work provides insight into both fundamental retention processes and applied system performance. The findings contribute to the development of infiltration basin designs that balance hydrologic functionality with proactive management of emerging contaminants.

## Reactive Media for PFAS Retention

The incorporation of reactive media into stormwater infiltration basin soils is intended to overcome the limited PFAS attenuation capacity of conventional sandy substrates. Effective reactive materials must exhibit high sorptive capacity, chemical stability under variable hydrologic conditions, and compatibility with infiltration system hydraulics. This study focuses on three classes of reactive media biochar, zeolite, and iron oxide which have demonstrated complementary PFAS adsorption characteristics and practical feasibility for field deployment.

### Biochar

Biochar is a porous, carbonaceous material derived from the thermal conversion of biomass under oxygen-limited conditions. Its suitability for PFAS retention is primarily attributed to its high specific surface area, aromatic carbon structure, and abundance of surface functional groups. These properties promote strong interactions with fluorinated organic compounds, particularly long-chain PFAS.

PFAS adsorption onto biochar is dominated by hydrophobic partitioning and van der Waals interactions between fluorinated carbon chains and graphitic carbon domains. Surface charge also plays a role, as electrostatic attraction can enhance retention under conditions where biochar surfaces are positively charged. Biochar produced at higher pyrolysis temperatures generally exhibits increased aromaticity and sorption capacity, although excessive graphitization may reduce surface functional group availability. When incorporated into infiltration basin soils, biochar improves PFAS retention while also contributing to soil structure and permeability.

### Zeolite

Zeolites are microporous aluminosilicate minerals characterized by a rigid crystalline framework and high cation exchange capacity. While zeolites have traditionally been applied for nutrient and metal removal, their use in PFAS mitigation has gained attention due to their tunable surface chemistry and ion exchange properties.

PFAS adsorption by zeolite occurs primarily through electrostatic interactions between negatively charged PFAS functional groups and positively charged exchange sites within the mineral lattice. Modified zeolites, particularly those treated to enhance surface hydrophobicity or cationic character, exhibit improved PFAS affinity. However, zeolite performance can be influenced by competing ions in stormwater, which may occupy exchange sites and reduce PFAS retention efficiency. Despite this limitation, zeolites provide a valuable adsorption pathway for PFAS species that exhibit weaker hydrophobic interactions.

### Iron Oxide

Iron oxide materials, including amorphous and crystalline forms, offer reactive surfaces capable of binding anionic contaminants through surface complexation mechanisms. Hydroxyl groups on iron oxide surfaces facilitate ligand exchange reactions with PFAS functional groups, particularly under acidic to neutral pH conditions commonly observed in stormwater.

Iron oxides also contribute to electrostatic attraction and can promote co-precipitation processes that enhance contaminant immobilization. When blended with carbon-based media, iron oxides improve the retention of PFAS species that are poorly adsorbed by hydrophobic interactions alone. Additionally, iron oxide amendments have been shown to increase the overall resilience of reactive soil systems by reducing desorption under fluctuating water chemistry.

The bar graph above illustrates the relative PFAS adsorption efficiency of the three reactive media evaluated. Biochar demonstrates the highest adsorption performance, reflecting its strong hydrophobic and surface interaction mechanisms.

## Synergistic Performance in Reactive Soil Mixes

The combined use of biochar, zeolite, and iron oxide within engineered soil matrices enables multiple adsorption mechanisms to operate simultaneously. This synergy reduces reliance on a single retention pathway and improves overall system robustness under variable stormwater loading conditions. Reactive soil mixes benefit from enhanced PFAS

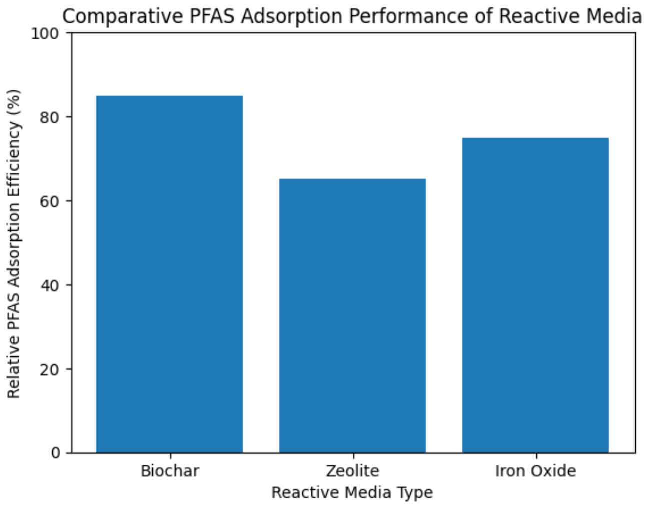

**Figure 1:** Comparative PFAS Adsorption Performance of Reactive Media

capture across a range of molecular chain lengths, while maintaining infiltration capacity and structural stability.

The complementary behavior of these materials supports their application in infiltration basin retrofits and new installations where groundwater protection is a priority.

## Adsorption Mechanisms

The effectiveness of reactive soil mixes for PFAS attenuation in stormwater infiltration basins is governed by a combination of interrelated adsorption mechanisms that depend on both PFAS molecular characteristics and reactive media surface properties. Unlike conventional pollutants that may be removed through biodegradation or precipitation, PFAS retention relies almost exclusively on physicochemical interactions at the solid–water interface. Understanding these mechanisms is critical for designing infiltration systems capable of sustained contaminant control.

### Hydrophobic Partitioning and Carbon Interactions

Hydrophobic partitioning is a dominant mechanism for PFAS adsorption onto carbon-rich materials, particularly biochar. Long-chain PFAS exhibit strong affinity for aromatic carbon surfaces due to their fluorinated alkyl chains, which interact with nonpolar domains within biochar pores. The extent of this interaction is influenced by biochar surface area, pore size distribution, and degree of aromaticity. Higher pyrolysis temperatures typically enhance graphitic structures, thereby increasing hydrophobic sorption capacity.

In reactive soil mixes, biochar acts as the primary sink for long-chain PFAS, reducing their mobility during infiltration events. However, hydrophobic partitioning alone is insufficient for effective removal of short-chain PFAS, which exhibit lower hydrophobicity and higher aqueous solubility.

### Electrostatic Interactions and Ion Exchange

Electrostatic attraction plays a critical role in the adsorption of anionic PFAS species, particularly those with sulfonate or carboxylate functional groups. Zeolite and iron oxide amendments provide positively charged surface sites that can attract negatively charged PFAS molecules under favorable pH conditions. Zeolites further contribute through ion exchange mechanisms, where PFAS displace weakly bound anions at exchange sites within the mineral framework.

The efficiency of electrostatic interactions is strongly dependent on stormwater chemistry. Elevated ionic strength and the presence of competing anions such as sulfate or nitrate can reduce PFAS adsorption by occupying available surface sites. Despite these limitations, electrostatic mechanisms are essential for attenuating short-chain PFAS that are otherwise poorly retained by carbon-based sorbents.

### Surface Complexation on Metal Oxides

Iron oxide amendments introduce reactive hydroxyl groups capable of forming surface complexes with PFAS functional groups. This mechanism is particularly effective for sulfonated PFAS, which exhibit stronger binding affinity through ligand exchange reactions. Surface complexation is sensitive to pH, with higher adsorption observed under acidic to neutral conditions where iron oxide surfaces maintain positive charge.

In blended soil systems, iron oxides complement carbon and zeolite components by stabilizing PFAS at mineral interfaces, thereby reducing desorption potential during fluctuating hydraulic conditions. This mechanism also enhances resistance to competitive displacement over repeated stormwater loading cycles.

### Synergistic Effects in Reactive Soil Mixes

The incorporation of multiple reactive media within a single soil matrix creates synergistic adsorption behavior that exceeds the performance of individual materials. Biochar preferentially retains long-chain PFAS through hydrophobic interactions, while zeolite and iron oxides target short-chain species through electrostatic attraction and surface complexation. This complementary functionality broadens the range of PFAS compounds effectively attenuated within infiltration systems.

Additionally, reactive soil mixes promote spatial distribution of adsorption sites, reducing localized saturation and extending sorbent lifespan. These synergistic effects are particularly important under field conditions where PFAS loading is variable and unpredictable.

Table 1 illustrates the complementary roles of individual reactive media and highlights the advantage of blended soil systems for comprehensive PFAS retention.

### Relative Contribution of Adsorption Mechanisms

Field and laboratory observations indicate that hydrophobic

**Table 1:** Dominant PFAS Adsorption Mechanisms Across Reactive Media

| *Reactive medium* | *Primary adsorption mechanisms* | *PFAS chain length most affected* | *Key influencing factors* |
|---|---|---|---|
| Biochar | Hydrophobic partitioning, pore filling | Long-chain PFAS | Surface area, aromaticity, pore structure |
| Zeolite | Electrostatic attraction, ion exchange | Short- to mid-chain PFAS | Surface charge, ionic strength, pH |
| Iron Oxide | Surface complexation, electrostatic interaction | Sulfonated PFAS | pH, hydroxyl group density |
| Blended Soil Mix | Combined hydrophobic, electrostatic, and complexation mechanisms | Broad PFAS spectrum | Media ratio, stormwater chemistry |

partitioning accounts for the largest proportion of PFAS removal in reactive soil mixes, particularly for long-chain compounds. Electrostatic interactions and surface complexation provide secondary but essential contributions, especially for short-chain and highly mobile PFAS species. The balance among these mechanisms determines overall system performance and resilience under variable environmental conditions.

Figure 2 illustrates the relative contribution of dominant adsorption mechanisms governing PFAS retention in reactive soil mixes. Hydrophobic partitioning represents the primary removal pathway, while electrostatic interaction and surface complexation provide critical complementary functions, particularly for short-chain and sulfonated PFAS.

## Field-Scale Demonstration and Monitoring

To evaluate the practical effectiveness of reactive soil mixes under operational conditions, a field-scale stormwater infiltration basin was selected for demonstration and performance assessment. The basin represented a typical urban infiltration system receiving runoff from mixed land-use catchments, including roadways and impervious surfaces known to contribute PFAS to stormwater flows. The system was retrofitted with a reactive treatment layer designed to enhance contaminant retention while preserving infiltration capacity.

### System Design and Reactive Soil Configuration

The infiltration basin was modified to include a stratified soil profile consisting of a surface pretreatment layer, a reactive soil layer, and an underlying drainage layer. The reactive layer comprised native sandy soil amended with biochar, zeolite, and iron oxide at proportions determined from preliminary adsorption testing. This blended configuration was selected to promote complementary adsorption mechanisms targeting a broad spectrum of PFAS compounds.

Hydraulic conductivity testing was conducted prior to installation to ensure that the amended soil met infiltration performance criteria. The reactive layer thickness was optimized to balance contact time with stormwater while avoiding excessive head loss. Construction procedures emphasized uniform mixing and compaction control to minimize preferential flow paths and ensure consistent treatment performance across the basin footprint.

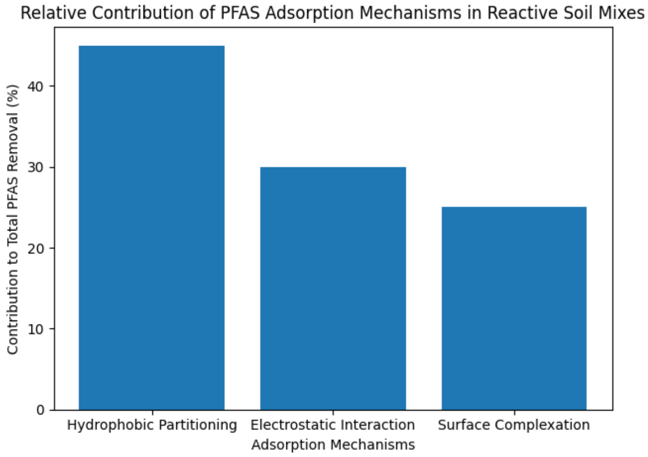

**Figure 2:** Relative Contribution of PFAS Adsorption Mechanisms in Reactive Soil Mixes

### Monitoring Strategy and Sampling Protocol

A comprehensive monitoring program was implemented to assess PFAS attenuation across the infiltration system. Influent stormwater samples were collected at basin entry points during multiple rainfall events to characterize incoming PFAS concentrations and chemical composition. Effluent samples were obtained from lysimeters and shallow groundwater monitoring wells positioned beneath the reactive layer to capture post-infiltration water quality.

Sampling events were designed to represent a range of storm intensities and antecedent dry conditions. Analytical methods targeted a suite of commonly detected PFAS, including both long-chain and short-chain compounds, to evaluate differential removal behavior. In addition to PFAS concentrations, supporting parameters such as pH, dissolved organic carbon, electrical conductivity, and major ions were measured to assess conditions influencing adsorption processes.

## Field Performance and PFAS Attenuation

Field monitoring results demonstrated a consistent reduction in PFAS concentrations following infiltration through the reactive soil layer. Long-chain PFAS exhibited the highest removal efficiencies, reflecting strong hydrophobic interactions with biochar and effective surface complexation on iron oxide minerals. Short-chain PFAS showed moderate attenuation, indicating partial retention through electrostatic interactions and ion exchange processes associated with zeolite and mineral surfaces.

Temporal analysis revealed stable performance across successive storm events, suggesting limited sorbent saturation under observed loading conditions. No significant decline in infiltration rate or surface clogging was observed during the monitoring period, confirming that the reactive amendments did not compromise basin hydraulics. These findings support the feasibility of integrating reactive soil mixes into stormwater infrastructure without sacrificing functional performance.

The table 3 compares mean influent PFAS concentrations with post-infiltration concentrations measured beneath the reactive soil layer and reports corresponding removal efficiencies. Distinctions between long-chain and short-chain PFAS highlight differences in adsorption behavior associated with compound chemistry.

## System Stability and Operational Considerations

Beyond contaminant removal, the long-term stability of reactive soil performance is critical for stormwater applications. Visual inspections and post-event assessments indicated minimal material migration or structural degradation within the reactive layer. The presence of iron oxide contributed to improved particle cohesion, while biochar enhanced porosity and internal surface area.

Potential influences of competing contaminants and seasonal variations in stormwater chemistry were also considered. Although organic matter and inorganic ions may compete for sorption sites, the multi-component soil mix appeared resilient to such effects due to the diversity of adsorption pathways. Periodic monitoring is recommended to assess sorbent aging and inform maintenance or replacement schedules where necessary.

## Implications for Field Implementation

The field-scale demonstration confirms that reactive soil mixes can be effectively integrated into stormwater infiltration basins as a passive treatment solution for PFAS mitigation. The observed performance highlights the importance of media selection, blend optimization, and proper construction practices. When designed appropriately, reactive infiltration systems provide a scalable and sustainable approach for reducing PFAS transport to groundwater while maintaining the hydrologic benefits of infiltration-based stormwater management.

## Implications for Stormwater Management

The integration of reactive soil mixes into stormwater infiltration basins carries significant implications for contemporary stormwater management, particularly in urban environments where emerging contaminants such as PFAS pose persistent threats to groundwater quality. Traditional infiltration systems primarily focus on hydrologic control, including peak flow attenuation and groundwater recharge, but often provide limited contaminant retention for highly mobile and chemically resistant compounds. The demonstrated effectiveness of reactive soil amendments underscores the potential for combining hydrologic and water quality objectives within a single infrastructure framework.

## Enhancement of Contaminant Control

Reactive soil mixes introduce complementary mechanisms that improve the retention of a broad spectrum of PFAS compounds. The inclusion of biochar, zeolite, and iron oxide within the soil matrix allows simultaneous exploitation of hydrophobic partitioning, electrostatic attraction, ion exchange, and surface complexation processes. This multi-mechanistic approach is particularly advantageous in urban runoff scenarios, where PFAS compositions are complex and highly variable. By incorporating such reactive layers, infiltration basins transition from passive conveyance structures to active treatment systems capable of reducing contaminant loadings before subsurface transport.

## Preservation of Hydraulic Functionality

A critical consideration in the application of reactive soil amendments is the preservation of hydraulic performance. Field-scale observations indicate that well-designed reactive soil layers can maintain infiltration rates while providing meaningful PFAS retention. This dual functionality ensures that retrofitted or newly constructed infiltration basins continue to meet peak flow control and groundwater recharge objectives without compromising operational reliability. Design parameters such as media proportions, layer thickness, and mixing homogeneity are essential to balancing hydraulic and contaminant removal performance.

## Adaptation to Site-Specific Conditions

The findings highlight the importance of tailoring reactive soil mixes to local site conditions. Variations in soil texture, stormwater chemistry, PFAS loading, and catchment characteristics can influence adsorption efficiency. For instance, high ionic strength or elevated organic matter in stormwater may reduce sorption capacity, necessitating adjustments in reactive media composition or thickness. Incorporating site-specific considerations during design enhances treatment performance while minimizing the risk of premature media saturation or failure.

### Contribution to Sustainable Urban Water Management

From a broader perspective, reactive soil mixes offer a sustainable and scalable solution for managing emerging contaminants in urban stormwater systems. By addressing both water quality and hydrologic objectives, such engineered solutions reduce the need for centralized treatment infrastructure, lower operational costs, and support integrated water resource management strategies. Moreover, reactive soil amendments can be coupled with other green infrastructure practices, including vegetated swales, retention ponds, and permeable pavements, to create multifunctional treatment landscapes that improve resilience and environmental performance.

### Guidance for Policy and Practice

The demonstrated effectiveness of reactive soil mixes provides actionable insights for engineers, planners, and policymakers seeking to mitigate PFAS risks in urban catchments. Incorporating engineered reactive layers into infiltration basin design guidelines, monitoring frameworks, and maintenance protocols can help ensure long-term contaminant retention while maintaining system functionality. These findings also highlight the need for ongoing monitoring and adaptive management, particularly as PFAS use patterns and stormwater compositions evolve over time.

## CONCLUSION

The study demonstrates that reactive soil mixes composed of biochar, zeolite, and iron oxide provide a robust strategy for mitigating PFAS transport in stormwater infiltration basins. Laboratory and field-scale assessments confirm that blended reactive media can effectively attenuate both long-chain and short-chain PFAS through complementary adsorption mechanisms, including hydrophobic partitioning, electrostatic attraction, ion exchange, and surface complexation. Field monitoring results indicate consistent reductions in PFAS concentrations without compromising infiltration performance, demonstrating the practical feasibility of integrating engineered reactive soils into existing stormwater infrastructure.

The multi-component soil approach addresses key challenges associated with PFAS mobility, particularly in sandy or low-organic soils that exhibit limited natural retention capacity. Furthermore, the system maintained hydraulic functionality, structural integrity, and operational stability across varying storm events, highlighting its suitability for long-term deployment in urban catchments.

The findings have broad implications for sustainable stormwater management, providing a scalable and passive treatment solution that balances water quality protection with hydrologic objectives. By incorporating reactive soil layers, infiltration basins can transition from passive conveyance systems to multifunctional treatment units capable of mitigating emerging contaminants. Future work should explore long-term sorbent aging, periodic maintenance requirements, and site-specific design optimization to maximize PFAS retention and ensure sustained performance.

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