RESEARCH ARTICLE

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Biochar-Enhanced Filtration Media For Multi-Pollutant Industrial Runoff

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Abstract

Industrial stormwater runoff represents a complex environmental challenge due to the simultaneous presence of heavy metals, per- and polyfluoroalkyl substances (PFAS), and excess nutrients. Conventional stormwater treatment systems are often designed to target single contaminant classes, limiting their effectiveness under mixed-pollutant conditions. This article examines the emerging role of engineered biochar as a multifunctional filtration medium capable of addressing diverse pollutant groups within industrial runoff. By tailoring feedstock selection, surface chemistry, and activation methods, biochar demonstrates high adsorption capacity for metals, strong affinity for PFAS compounds, and significant nutrient retention potential. The mechanisms governing these interactions, system design considerations, and performance implications for industrial stormwater management are critically evaluated. The findings highlight biochar-enhanced filtration systems as a scalable and sustainable solution for improving runoff quality and regulatory compliance in industrial environments.

Keywords: Biochar filtration, industrial stormwater, PFAS removal, heavy metals adsorption, nutrient control, runoff treatment

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Introduction

Industrial stormwater runoff has emerged as a critical pathway for the transport of complex pollutant mixtures into surface and groundwater systems. Unlike municipal runoff, which is often dominated by sediments and nutrients, industrial runoff frequently contains elevated concentrations of heavy metals, persistent organic contaminants, and process-related chemical residues. These pollutants originate from material handling areas, equipment corrosion, vehicular traffic, storage yards, atmospheric deposition, and exposed industrial surfaces. During precipitation events, accumulated contaminants are rapidly mobilized, resulting in episodic but highly concentrated discharges that challenge conventional treatment infrastructures.

Heavy metals such as zinc, copper, chromium, and lead are among the most prevalent inorganic contaminants in industrial runoff. Even at low concentrations, these metals can exert toxic effects on aquatic organisms, disrupt biogeochemical cycles, and accumulate in sediments and food webs. In parallel, per- and polyfluoroalkyl substances (PFAS) have gained increasing attention due to their widespread industrial use, environmental persistence, and potential human health impacts. Their strong carbon–fluorine bonds render them resistant to natural degradation processes, allowing them to persist in stormwater systems and migrate into downstream environments.

Nutrient species, particularly nitrogen and phosphorus compounds, further complicate industrial runoff management. While nutrients are often associated with agricultural or urban sources, industrial activities contribute significant nutrient loads through cooling water discharges, chemical processing, and surface wash-off. Excessive nutrient inputs promote eutrophication in receiving waters, leading to algal blooms, oxygen depletion, and ecosystem degradation. The simultaneous presence of metals, PFAS, and

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nutrients necessitates treatment approaches capable of addressing diverse contaminant classes within a single system.

Traditional stormwater treatment practices are generally designed to target specific pollutants, relying on sedimentation, filtration, or chemical precipitation mechanisms. While effective for particulate-bound contaminants, these methods often exhibit limited efficiency for dissolved metals, persistent organic compounds, and highly mobile nutrients. The deployment of multiple treatment units to address individual pollutant groups increases system complexity, operational costs, and maintenance demands, particularly in space-constrained industrial settings.

In response to these limitations, research and practice have increasingly focused on multifunctional treatment media capable of providing broad-spectrum pollutant removal. Biochar has emerged as a particularly promising material in this context. Produced through the controlled thermal conversion of biomass, biochar exhibits a porous carbon matrix with high surface area, variable surface charge, and diverse functional groups. These characteristics enable biochar to interact with a wide range of contaminants through adsorption, ion exchange, and surface complexation processes.

Advancements in biochar engineering have further enhanced its applicability for industrial stormwater treatment. By manipulating feedstock selection, thermal processing conditions, and post-production modifications, biochar properties can be tailored to improve affinity for specific contaminant classes. This tunability positions engineered biochar as a versatile filtration medium capable of simultaneously addressing metals, PFAS, and nutrients within integrated stormwater systems.

Properties of Engineered Biochar Relevant to Runoff Treatment

The performance of biochar as a filtration medium in industrial stormwater systems is fundamentally governed by its physicochemical properties, which can be deliberately engineered to enhance multi-pollutant removal. Unlike conventional granular media, biochar offers a tunable structure and surface chemistry that allow it to interact effectively with diverse contaminant classes present in industrial runoff.

Feedstock Selection and Carbon Matrix Structure

The choice of biomass feedstock plays a central role in defining the structural and chemical characteristics of biochar. Agricultural residues, wood-based materials, and industrial by-products each impart distinct elemental compositions and ash contents. Lignin-rich feedstocks generally produce biochar with higher aromatic carbon content, contributing to structural stability and enhanced affinity for hydrophobic organic contaminants such as PFAS. In contrast, mineral-rich feedstocks yield biochars with greater inorganic fractions, which can promote metal immobilization through precipitation and surface complexation mechanisms.

The resulting carbon matrix forms a hierarchical pore network composed of micro-, meso-, and macropores. This pore architecture influences both contaminant accessibility and hydraulic performance when biochar is deployed in filtration systems. Well-developed pore structures facilitate rapid diffusion of dissolved pollutants while maintaining sufficient permeability for stormwater flow.

Pyrolysis Conditions and Surface Area Development

Thermal processing conditions strongly influence biochar surface area, porosity, and functional group distribution. Higher thermal conversion temperatures typically increase surface area and pore volume by driving off volatile compounds and reorganizing carbon structures. These properties are particularly beneficial for the adsorption of organic pollutants, where increased surface area enhances hydrophobic partitioning.

Lower-temperature biochars, while exhibiting comparatively reduced surface area, retain a greater abundance of oxygen-containing functional groups such as carboxyl, hydroxyl, and carbonyl moieties. These functional groups provide active sites for electrostatic attraction and complexation with metal ions and nutrient species. The ability to balance surface area and chemical reactivity through controlled processing is a defining advantage of engineered biochar.

Surface Chemistry and Functional Group Distribution

Surface functional groups are critical to biochar's interaction with dissolved contaminants in industrial runoff. Negatively charged functional sites enhance the adsorption of positively charged metal ions through electrostatic attraction and ion exchange processes. At the same time, polar surface domains support nutrient retention, particularly for ammonium and phosphate species.

Engineered biochars often exhibit heterogeneous

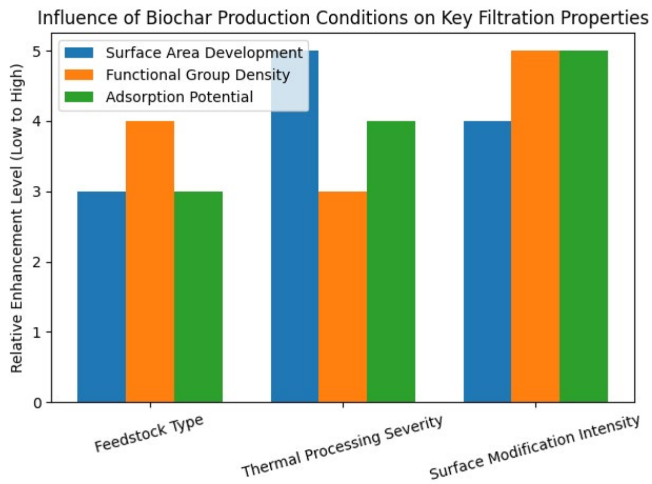

Figure 1: This graph illustrates how variations in biochar engineering parameters influence key filtration properties. Differences in feedstock type, thermal processing severity, and surface modification intensity are shown to affect surface area development, functional group density, and overall adsorption potential, highlighting the role of production conditions in optimizing biochar filtration performance.

surface charge distributions, allowing them to interact with both anionic and cationic contaminants under varying pH conditions. This versatility is especially important in industrial stormwater systems, where influent chemistry may fluctuate during storm events.

Post-Production Modification and Activation

Post-production modification techniques significantly expand the functional performance of biochar. Chemical activation increases pore accessibility and surface reactivity, while metal oxide impregnation enhances phosphate binding and PFAS adsorption. These modifications introduce additional reactive sites without compromising hydraulic conductivity when biochar is used as a filtration medium.

Such engineered enhancements enable biochar to function as a single, integrated treatment medium rather than requiring multiple specialized layers. This property reduces system complexity and improves feasibility for retrofitting existing industrial stormwater infrastructure.

Hydraulic Compatibility and Structural Stability

For practical deployment, biochar must maintain structural integrity under variable flow conditions. Engineered biochar particles exhibit sufficient mechanical strength to resist fragmentation while preserving high permeability when blended with sand or aggregate. This balance ensures consistent treatment performance without excessive head loss, even during high-intensity storm events.

Mechanisms of Multi-Pollutant Removal

The ability of engineered biochar to simultaneously remove diverse contaminants from industrial runoff is rooted in the coexistence of multiple physicochemical and biologically mediated mechanisms. Unlike conventional filtration media that rely on a single dominant process, biochar operates as a multifunctional sorbent, enabling concurrent removal of metals, persistent organic compounds, and nutrients under dynamic stormwater conditions.

Heavy Metal Removal Mechanisms

Heavy metals in industrial runoff are predominantly present in dissolved or weakly complexed forms, making them difficult to capture through sedimentation-based systems. Engineered biochar facilitates metal removal through surface complexation, ion exchange, and mineral-assisted precipitation.

Oxygen-containing functional groups on the biochar surface form stable inner-sphere complexes with metal ions such as zinc, copper, and lead. This process immobilizes metals within the biochar matrix and reduces their mobility in downstream environments. Additionally, the inherent cation exchange capacity of biochar allows divalent and trivalent metal ions to replace weaker bound cations on the surface. In mineral-rich biochars, embedded ash components promote localized precipitation reactions, further enhancing metal retention under varying pH conditions.

PFAS Adsorption Mechanisms

PFAS compounds exhibit high environmental persistence and low reactivity, necessitating adsorption-based treatment approaches. Biochar addresses this challenge primarily through hydrophobic partitioning and electrostatic interactions. The aromatic carbon framework of engineered biochar provides non-polar domains that favor the accumulation of fluorinated organic molecules, particularly long-chain PFAS species.

Surface charge modification further improves PFAS adsorption by attracting negatively charged PFAS functional groups to positively charged biochar sites. Pore size distribution also plays a critical role, as microporous structures increase contact between PFAS molecules and sorption sites. These combined mechanisms enable effective PFAS capture without

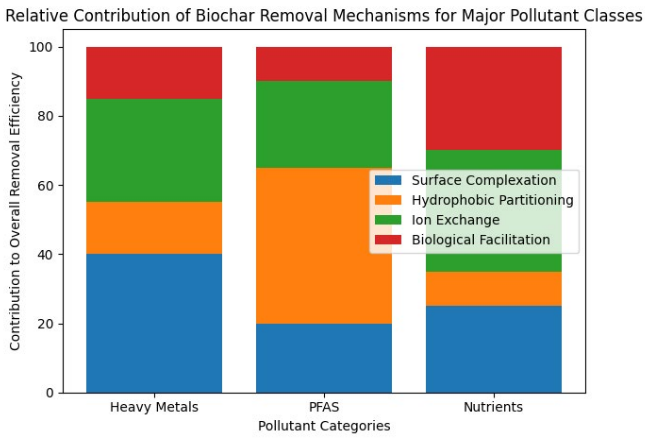

Figure 2: This graph illustrates the relative contributions of four key removal mechanisms: surface complexation, hydrophobic partitioning, ion exchange, and biological facilitation in biochar-mediated treatment of major pollutant classes.

reliance on chemical degradation pathways.

Nutrient Retention and Transformation

Nutrient removal in biochar-based systems occurs through both physicochemical adsorption and biologically mediated transformation. Ammonium ions are retained via cation exchange processes, while phosphate removal is achieved through ligand exchange with metal oxides present on biochar surfaces. Engineered biochars enriched with iron or aluminum compounds exhibit particularly strong phosphate binding capacity.

Beyond adsorption, biochar creates microhabitats that support microbial colonization. These microbial communities enhance nitrification and denitrification processes, facilitating the transformation of dissolved nitrogen species into less bioavailable forms. This dual functionality allows biochar filters to address both immediate nutrient loads and longer-term ecological impacts.

Synergistic and Competitive Interactions

In mixed-pollutant systems, interactions between contaminants influence overall removal efficiency. Engineered biochar mitigates competitive sorption through spatial separation of functional sites and heterogeneous surface chemistry. While metals preferentially bind to polar functional groups, organic contaminants occupy hydrophobic domains, reducing direct competition for sorption sites.

These synergistic interactions allow biochar to maintain stable performance across fluctuating contaminant concentrations typical of industrial stormwater events. The capacity to accommodate multiple pollutants within a single filtration medium represents a significant advancement over conventional treatment materials.

Table 1 summarizes the dominant removal mechanisms of engineered biochar for key pollutant classes commonly found in industrial stormwater runoff.

Implications for System Design

Understanding the mechanisms governing multi-pollutant removal informs the design of biochar-enhanced stormwater systems. Media selection and modification strategies can be optimized to target site-specific contaminant profiles. By leveraging complementary removal pathways within a single filtration medium, engineered biochar enables compact system designs with high treatment efficiency and operational resilience.

Integration into Industrial Stormwater Systems

The successful deployment of engineered biochar in industrial stormwater systems requires careful consideration of hydraulic performance, pollutant load characteristics, and operational constraints. Biochar-enhanced filtration media can be integrated into various stormwater control structures, providing a scalable and multifunctional approach to multi-pollutant treatment.

System Configurations and Media Placement

Biochar can be incorporated into multiple system configurations depending on site-specific requirements:

- Filtration Basins: Biochar can be layered with gravel or sand to create high-contact filtration beds. This configuration enables removal of both dissolved and particulate-bound contaminants while maintaining adequate hydraulic conductivity.
- Permeable Reactive Barriers (PRBs): PRBs installed in drainage channels allow stormwater to pass through biochar-filled trenches, providing extended contact time for adsorption and microbial-mediated nutrient transformation.
- Cartridge or Modular Filters: For high-flow industrial applications or retrofitting existing drainage systems, biochar-packed cartridges or modular units provide rapid pollutant removal with minimal footprint.

Blending biochar with coarser media prevents clogging and ensures uniform flow distribution. Particle size distribution, media depth, and hydraulic retention time

Table 1: Dominant Removal Mechanisms of Engineered Biochar for Key Industrial Runoff Pollutants

Pollutant Category	*Dominant Removal Mechanisms*	*Key Biochar Properties Involved*	*Treatment Outcome*
Heavy Metals	Surface complexation, ion exchange, precipitation	Oxygen functional groups, mineral content, cation exchange capacity	Immobilization and reduced bioavailability
PFAS	Hydrophobic partitioning, electrostatic attraction	Aromatic carbon structure, surface charge, microporosity	Persistent compound adsorption
Nutrients (N, P)	Adsorption, ligand exchange, microbial transformation	Surface functional groups, metal oxides, biofilm support	Load reduction and transformation
Mixed Pollutants	Synergistic sorption processes	Heterogeneous surface chemistry	Stable multi-pollutant removal

are critical design parameters that directly influence removal efficiency for metals, PFAS, and nutrients.

Hydraulic Considerations and Flow Management

Industrial stormwater systems are subject to highly variable flow rates, including intense episodic storm events. Engineered biochar media must therefore balance pollutant adsorption capacity with hydraulic performance. Oversizing media layers and incorporating pre-treatment sedimentation zones reduce the risk of media fouling and ensure consistent contaminant removal.

Flow distribution structures such as perforated plates, weirs, or flow spreaders are recommended to maintain even water contact across the biochar layer. Hydraulic retention time can be adjusted to optimize pollutant interactions, with longer residence times enhancing adsorption of PFAS and metals, and promoting nutrient transformation through microbial processes.

Operational Considerations and Maintenance

Operational longevity is a key consideration for industrial stormwater systems. Engineered biochar demonstrates high stability under variable flow and contaminant loading, but periodic inspection and maintenance are necessary to prevent channeling, clogging, or media exhaustion.

Table 2 This table presents key operational and design parameters for biochar-enhanced industrial stormwater filtration systems. It outlines recommended ranges for media depth, hydraulic retention time, biochar blending ratios, and maintenance frequency, and explains how each parameter influences pollutant removal performance

Performance Optimization Strategies

Blending biochar with complementary media and site-specific customization enhances overall system effectiveness. For instance, incorporating gravel or coarse sand improves drainage and prevents compaction, while the addition of metal oxides or activated biochar can increase affinity for specific pollutants.

Table 3 This table compares common biochar-based stormwater filtration configurations used in industrial settings, including filtration basins, permeable reactive barriers, cartridge filters, and hybrid systems.

Implications for Industrial Stormwater Management

Integrating biochar into industrial runoff treatment systems provides a sustainable and multifunctional approach. Its flexibility in configuration allows for retrofitting existing infrastructure or designing new systems with high pollutant removal efficiency. Moreover, by leveraging biochar's simultaneous removal of metals, PFAS, and nutrients, industrial

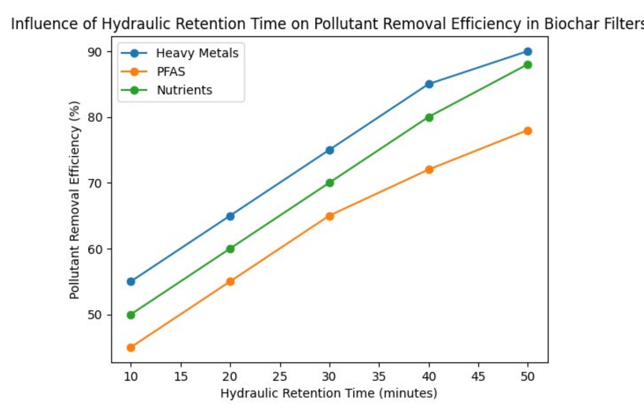

Figure 3: This graph illustrates the influence of hydraulic retention time on pollutant removal efficiency in biochar filtration systems. The results show a consistent increase in removal efficiency for heavy metals, PFAS, and nutrients as hydraulic retention time increases from 10 to 50 minutes.

Table 2: Operational Considerations and Maintenance

Parameter	*Recommended Range / Design Consideration*	*Impact on Pollutant Removal*
Media Depth	0.5–1.0 m (adjustable per pollutant load)	Increases contact time and adsorption efficiency
Hydraulic Retention Time	15–60 min	Enhances PFAS and metal removal, supports nutrient transformation
Biochar-Sand Ratio	1:2 to 1:4	Maintains permeability while preserving adsorption capacity
Flow Distribution	Even flow via spreaders or weirs	Reduces channeling, improves media utilization
Maintenance Frequency	6–12 months	Ensures consistent hydraulic and treatment performance

Table 3: Performance Optimization Strategies

System Type	*Configuration*	*Target Pollutants*	*Key Advantages*	*Limitations*
Filtration Basin	Layered biochar-sand-gravel bed	Metals, PFAS, nutrients	High removal efficiency, adaptable to site	Requires larger footprint
Permeable Reactive Barrier	Biochar trench along drainage	Metals, nutrients	Long contact time, passive operation	Space-intensive
Cartridge/Modular Filter	Biochar-packed cartridges	PFAS, metals	Compact, easy retrofitting	Limited lifespan per cartridge
Hybrid System	Biochar + sand + metal-oxide amendment	Metals, PFAS, nutrients	Optimized multi-pollutant removal	Higher material cost

facilities can meet regulatory discharge standards while minimizing operational complexity. Properly designed and maintained biochar-based systems offer long-term performance reliability, reduced maintenance costs, and potential carbon co-benefits through biochar utilization.

Environmental and Regulatory Implications

The adoption of biochar-enhanced filtration media for industrial stormwater treatment carries significant environmental and regulatory implications. By addressing multiple pollutant classes within a single system, engineered biochar contributes to improved water quality outcomes while supporting compliance with increasingly stringent discharge requirements. Its multifunctional performance positions it as a strategic solution at the intersection of environmental protection, regulatory compliance, and sustainable industrial practice.

From an environmental perspective, the simultaneous removal of heavy metals, PFAS, and nutrients reduces the cumulative stress imposed on receiving water bodies. Metals captured within biochar matrices are immobilized, limiting their bioavailability and potential for trophic transfer in aquatic ecosystems. The effective adsorption of PFAS mitigates the downstream persistence of these compounds, reducing long-term exposure risks to both ecological receptors and human populations relying on surface or groundwater resources. Nutrient retention and transformation further limit eutrophication potential, helping to preserve dissolved oxygen levels and aquatic biodiversity.

Biochar-based stormwater treatment systems also contribute to broader sustainability objectives. Biochar is typically produced from waste biomass streams, promoting resource recovery and circular material use. Its stable carbon structure supports long-term carbon sequestration, offering ancillary climate-related benefits when integrated into stormwater infrastructure. Additionally, the reuse or safe containment of spent biochar minimizes secondary environmental impacts associated with disposal, further enhancing the life-cycle sustainability of these systems.

From a regulatory standpoint, industrial stormwater discharges are subject to permit conditions that increasingly emphasize pollutant load reductions rather than solely concentration-based limits. Biochar-enhanced filtration systems provide a flexible means of achieving compliance across multiple regulated parameters without the need for separate treatment units. This integrated approach simplifies monitoring and reporting requirements while reducing the operational burden on industrial facilities.

The adaptability of engineered biochar also supports site-specific compliance strategies. Media properties can be tailored to address dominant pollutant profiles, allowing facilities to respond proactively to regulatory changes or evolving discharge standards. This flexibility is particularly valuable in industrial sectors subject to heightened scrutiny for PFAS and metal discharges, where treatment reliability and consistency are critical. Beyond compliance, the implementation of biochar-based stormwater systems reflects a shift toward preventive and performance-based environmental management. By incorporating treatment directly into runoff pathways, these systems reduce reliance on end-of-pipe solutions and enhance resilience to extreme storm events. The demonstrated capacity of biochar to maintain performance under variable hydraulic and chemical conditions strengthens its role as a robust regulatory compliance tool.

Overall, the environmental and regulatory implications of biochar-enhanced filtration media extend beyond pollutant removal alone. Their integration into industrial stormwater management frameworks supports ecological protection, regulatory efficiency, and sustainable infrastructure development. As regulatory expectations continue to evolve toward holistic and adaptive water quality management, engineered biochar systems offer a practical and forward-looking solution for industrial runoff control.

Conclusion

This article has examined the role of engineered biochar as an advanced filtration medium for addressing the complex pollutant mixtures characteristic of industrial stormwater runoff. The findings demonstrate that biochar's unique combination of porous structure, tunable surface chemistry, and multifunctional adsorption mechanisms enables simultaneous removal of heavy metals, PFAS, and nutrients within integrated stormwater treatment systems. This capability addresses a critical limitation of conventional treatment approaches that are often constrained to single-pollutant targets.

The effectiveness of biochar-enhanced filtration media is closely linked to deliberate engineering of feedstock selection, thermal processing conditions, and post-production modification. These factors collectively govern adsorption capacity, hydraulic compatibility, and long-term stability under variable flow and contaminant loading conditions. When properly designed and integrated, biochar systems exhibit consistent performance, operational resilience, and adaptability across diverse industrial environments.

Beyond treatment efficiency, biochar-based stormwater systems offer meaningful environmental and regulatory advantages. By reducing pollutant loads at the source, these systems mitigate downstream ecological impacts, support compliance with discharge requirements, and contribute to sustainable industrial water management practices. The use of biochar derived from waste biomass further reinforces circular resource utilization and enhances the environmental value of stormwater infrastructure investments.

The integration of biochar into industrial stormwater systems represents a shift toward multifunctional, performance-driven treatment strategies. Rather than relying on fragmented or sequential treatment units, biochar enables compact and cohesive designs capable of addressing emerging and legacy contaminants simultaneously. This integrated approach improves system efficiency while reducing operational complexity and long-term management costs.

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