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Biochar-Based Treatment Technologies for PFAS Removal from Industrial Storamwater and Wastewater: Mechanisms, Field Applications, and Future Regulatory Implications

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Abstract

Per- and polyfluoroalkyl substances (PFAS) represent a critical emerging contaminant class due to their extreme persistence, bioaccumulation potential, and documented adverse health effects in humans and wildlife. Biochar, a pyrolytic carbonaceous material derived from renewable biomass, has emerged as a promising sustainable and cost-effective adsorbent for PFAS removal from industrial stormwater and wastewater. This review synthesizes current knowledge on biochar-based treatment technologies for PFAS remediation, encompassing adsorption mechanisms, surface modification strategies, field-scale applications, and regulatory frameworks. Biochar's high microporous volumes (0.1–1.0 cm^3/g), aromaticity, and surface oxygen-containing functional groups make it effective for PFAS adsorption. (Chavan et al., 2024) The adsorption mechanism is composed mainly of electrostatic interaction between positively charged biochar and deprotonated PFAS, hydrogen bonding between anionic species of PFAS and functional groups, and hydrophobic interaction between long-chain hydrophobic PFAS and biochar, with electrostatic interaction playing a major role in acidic media. (Zhang et al., 2023) Despite biochar's advantages, challenges remain in achieving complete defluorination, managing short-chain PFAS, optimizing regeneration, and scaling field applications. This review identifies key research gaps, technological barriers, and opportunities for integrating biochar technologies into comprehensive treatment trains to address the growing regulatory pressures and environmental risks posed by PFAS contamination globally.

Keywords: PFAS; biochar; adsorption; wastewater treatment; stormwater; remediation; surface modification; regulatory compliance; emerging contaminants

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) represent a class of over 4,700 synthetic chemicals with exceptional chemical and thermal stability that have been used extensively in industrial and consumer applications since the 1950s. The widespread use of PFAS in nonstick cookware,

hydrophobic textiles, stain-resistant fabrics, cosmetics, and floor coverings has led to their persistent presence in wastewater streams, posing significant human health and ecological risks. (Chavan et al., 2024) PFAS are a group of over 4700 heterogeneous compounds with amphipathic properties and exceptional stability to chemical and thermal degradation, and have been exploited for almost 60 years and has largely contributed to their wide applicability over a vast range of industrial, professional and non-professional uses. (Panieri et al., 2022)

The global PFAS crisis has intensified due to their ubiquitous environmental distribution, documented bioaccumulation, and association with serious health effects. PFAS have received increasing scientific and political attention in recent years, with several thousand commercially produced compounds used in numerous products and technical processes; humans and other life forms are increasingly exposed to these substances due to their extreme persistence in the environment. (Brunn et al., 2023) Exposure to PFAS is linked to adverse reproductive outcomes and elevated blood pressure in pregnant individuals, and it negatively impacts aquatic ecosystems, particularly algal populations and microbial communities. (Chavan et al., 2024)

Traditional treatment approaches have proven inadequate for PFAS remediation. Hydrophobicity and electrostatic interactions are revealed to be the primary mechanisms for the elimination of PFAS; the efficiency of all techniques to eradicate short-chain PFAS is comparatively lower compared to long-chain PFAS; destruction techniques are the most efficient but have some drawbacks, including the formation of PFAS precursors and high operational costs; it is anticipated that combined methods will be required to effectively remediate PFAS-contaminated water. (Amen et al., 2023) Biochar, a renewable carbonaceous material produced through pyrolysis of biomass, offers a promising alternative due to its cost-effectiveness, sustainability, and demonstrated effectiveness in removing diverse PFAS classes from aqueous environments.

2. PFAS Chemistry, Sources, and Environmental Fate

2.1 Chemical Structure and Classification

PFAS compounds are characterized by a carbon backbone fully or partially substituted with fluorine atoms, combined with a functional head group such as carboxylic acid (-COOH), sulfonic acid (-SO_3H), or other moieties. This unique structure confers exceptional resistance to biological, chemical, thermal, and photochemical degradation. The best studied PFAS are carboxylic and sulfonic acids with chain lengths of C4 to C14, particularly perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS). (Brunn et al., 2023)

PFAS are conventionally categorized into two main classes: long-chain PFAS (≥C8) such as PFOA and PFOS, which have been used historically in manufacturing, and short-chain PFAS (C4-C7) such as perfluorobutanoic acid (PFBA) and perfluorobutane sulfonic acid (PFBS), which serve as replacements for legacy long-chain compounds. As the substitutes of legacy long-chain per-/polyfluoroalkyl substances (PFASs), short-chain PFASs have been widely detected in the environment; compared to long-chain PFASs, short-chain PFASs have smaller molecules and are more hydrophilic, therefore, they are more likely to experience long-distance transport and pose lasting environmental impacts. (Liu et al., 2024)

2.2 Major Sources and Environmental Occurrence

Current technologies largely focus on separation (sorption, ion exchange, or sequestration); due to diversity in PFAS properties, effective treatment will likely require treatment trains. (Simon et al., 2019) Key anthropogenic sources of PFAS contamination include aqueous film-forming foams (AFFFs) used for firefighting and training at military installations, airports, and industrial sites; manufacturing facilities producing PFAS-containing products; wastewater treatment plants that concentrate PFAS from municipal sewage; and landfill leachates. Many military bases and their surrounding communities are impacted by contamination with per- and polyfluoroalkyl substances (PFAS) from Aqueous Film-Forming Foams (AFFFs). (Darlington et al., 2018)

PFAS occurrence and transformation in various media, along with potential human exposure routes, are significant concerns; the varied toxicology and insufficient definition of PFAS exposure rate are among the main factors contributing to regulatory discrepancies; although it is agreed that PFASs pose potential health risks in various media, the link between the extent of PFAS exposure and the significance of PFAS risk remain among the evolving research areas. (Abunada et al., 2020)

2.3 PFAS Fate and Transport

PFAS mobility in groundwater and surface water is significantly higher than many classical persistent organic pollutants, owing to their hydrophilic character (particularly short-chain homologs), weak sorption to soil minerals, and resistance to biotransformation. Knowledge of PFAS fate and transport in the urban water cycle between water treatment plants (WTPs) and wastewater treatment plants (WWTPs) is dependent upon analytical methodology; system-wide mass balances are a daunting challenge that have not been achieved to date, complicated by the continued existence of legacy PFAS and the constantly moving target of newly emerging commercial PFAS and transformation products. (Winchell et al., 2021)

3. Biochar: Production, Properties, and Characterization

3.1 Biochar Production and Pyrolysis Methods

Biochar can alleviate several issues and should be inexpensive to produce; most biochars have a high pore structure and diverse functional groups that assist in the adsorption process. (Nur Salsabila Kamarudin et al., 2021) Biochar is primarily produced through pyrolysis, an oxygen-limited thermal decomposition of biomass, typically conducted at temperatures between 300–900°C. Pyrolysis at high temperatures generally produces hydrophobic biochars with higher surface area and micropore volume, allowing it to be more suitable for organic contaminants sorption, whereas biochars produced at low temperatures own smaller pore size, lower surface area, and higher oxygen-containing functional groups and are more suitable to remove inorganic contaminants. (Enaime et al., 2020)

Various feedstock materials can be converted to biochar, including agricultural residues, wood waste, sewage sludge, food waste, and other biomass sources. Sewage sludge to produce biochar-

based sorbents for per- and polyfluoroalkyl substances (PFAS) removal from water and soil may be an economically and environmentally sustainable waste management option. (Krahn et al., 2022) Pyrolysis is the process whereby carbonaceous materials, such as biosolids, are heated between 400°C and 900°C in the absence of oxygen; three main products are generated: a solid product called biochar, a py-liquid that consists of aqueous phase and non-aqueous phase liquid, and py-gas. (McNamara et al., 2023)

3.2 Effect of Pyrolysis Temperature on Biochar Properties

High pyrolysis temperature promotes the production of biochar with a strongly developed specific surface area, high porosity, pH as well as content of ash and carbon, but with low values of cation exchange capacity (CEC) and content of volatile matter; this is most likely due to significant degree of organic matter decomposition. (Tomczyk et al., 2020) The increasing temperature increased the content of fixed carbon (C), the C content and inorganic minerals (K, P, Fe, Zn, Ca, Mg), while the yield, the content of volatile matter (VM), O and H, cation exchange capacity, and the ratios of O/C and H/C decreased; highest pH and ash content were observed at intermediate temperatures; the number of acidic functional groups decreased as a function of pyrolysis temperature, especially for the carboxylic functional groups, while a reverse trend was found for the basic functional groups; at higher temperature, the specific surface area and pore volume are higher mostly due to the increase of the micropore surface area and micropore volume. (Zhao et al., 2017)

3.3 Physicochemical Properties Governing PFAS Sorption

To better characterize properties governing the sorption of per- and polyfluoroalkyl substances (PFAS) to biochar, twenty-three diverse biochars were characterized and evaluated as sorbents for perfluorooctanoic acid (PFOA); sludge-based biochars outperformed wood biochars as PFOA sorbents; multivariate statistical analysis revealed that the sorption capacity was mainly controlled by pore volume within the pore diameter region that could accommodate the molecular size of PFOA (3-6 nm); hydrophobic interactions between PFOA and aromatic carbon rich regions controlled sorption affinity, especially in the wood biochars. (Skjennum et al., 2024)

4. PFAS Adsorption Mechanisms on Biochar

4.1 Primary Adsorption Mechanisms

The adsorption mechanism is composed mainly of three aspects: (I) electrostatic interaction between the positively charged biochar and the deprotonated PFAS; (II) hydrogen bonding between anionic species of PFAS and functional groups; and (III) hydrophobic interaction between long-chain hydrophobic PFAS and biochar, with electrostatic interaction playing a major role in the three main adsorption mechanisms under acidic media. (Zhang et al., 2023)

The sorption of PFAS increased with greater fluorinated chain length, suggesting that hydrophobic interactions play a major role in sorption and electrostatic interactions a minor one; the CORG/O molar ratio and the specific surface area of the material were the two main sorbent properties

affecting PFAS sorption; dissolved organic carbon (DOC) content in solution had a negative effect on PFAS sorption. (Fabregat-Palau et al., 2022)

4.2 Chain-Length Dependent Sorption Behavior

PFASs sorption on both GAC and biochar were well represented by the pseudo-second-order model; the PFAS sorption capacity was chain-length dependent with following order: PFOS > PFOA > PFBS > PFBA; GAC exhibited high maximum Langmuir sorption capacity for both PFOS (123.5 μmol g−1) and PFOA (86.2 μmol g−1), which were 43% and 39.6% greater than biochar; the sorption mechanisms involved both electrostatic attraction and hydrophobic interaction; the sorption of PFASs increased with the decrease in pH; competitive sorption of PFASs occurred during the sorption process, resulting in decreased PFASs removal efficiencies. (Zhang et al., 2019)

PFAS sorption to colloidal activated carbon (CAC) was evaluated with removal rates between 41% and 100%; differences were noticed among the various spiking mixtures, based on perfluorocarbon chain length, functional group, and the starting PFAS concentrations; competition effects were detected when PFAS were in a multi-solute system, with an average 10% drop in removal; the PFAS most vulnerable to competition effects in multi-solute systems were the short-chain perfluoropentanoic acid (PFPeA) and perfluorobutane sulfonic acid (PFBS), with an up to 25% reduction in removal. (Niarchos et al., 2023)

4.3 Impact of Water Chemistry on Adsorption

The sorption and especially desorption of PFAS in the adsorbents was impacted by the pH, index ion, and ionic strength of simulated groundwater, especially for the short chain PFAS, with only minimal impacts compared to ROAC (reactive organic amendment carbon); although the potential mineral and charged constituents of the adsorbents contributed to the adsorption of short chain PFAS through electrostatic interactions, these interactions were susceptible to variable groundwater chemistry; hydrophobic interactions also played a major role in facilitating and increasing PFAS sorption, especially in adsorbents with aliphatic functional groups. (Umeh et al., 2023)

5. Biochar Modification and Enhancement Strategies

5.1 Acid and Base Modifications

Biochar can be considered a cost-effective and eco-friendly alternative to conventional adsorbents; with abundant feedstocks and favorable physicochemical properties, biochar shows significant potential to be applied as an adsorbent for removing contaminants from water; some modifications have been introduced to overcome limitations and improve biochar's adsorption capacity for PFAS; these include preparation conditions, including the pyrolysis process, activation, and modification techniques applied to biochar to enhance its adsorption capacity for different types of PFAS. (Behnami et al., 2024)

5.2 Metal and Metal Oxide Incorporation

A new method to synthesize magnetic sorbents by wet ball-milling with $FeCl_3$ solution and high-temperature carbonization can tailor a magnetic porous Fe-doped graphitized biochar (Fe-M−BC_{900}) that contains abundant dispersed positive iron sites with stable Fe^0/Fe_3C, multi-stage pore structure, highly hydrophobic graphite-like carbon, and O-containing functional groups; Fe-M−BC_{900} exhibited a high sorption capacity of 10.1 mg PFBA/g and 39.1 mg PFOA/g; PFAS sorption was mainly governed by pore-filling, electrostatic interaction, and hydrophobic partitioning; Fe-M−BC_{900} performed high co-removal rates (>96 %) for a wide range of legacy and emerging PFAS with different chain lengths and functional groups in natural waters and simulated wastewater, with a high relative sorption capacity of > 91 %, even after four consecutive recycling processes. (Liu et al., 2023)

A $FeCl_3$-activated dairy manure-derived biochar (Fe@MBC) was prepared via one-step pyrolysis/activation; the maximum adsorption capacity of Fe@MBC for PFOA (233 $mg \cdot g^{-1}$) was five times higher than that of pristine manure-derived biochar (P-MBC) (46 $mg \cdot g^{-1}$); PFOA adsorption was favorable at low solution pH and was independent on ionic strength, which supported the major contribution by inner-sphere complexation rather than out-sphere complexation; Fe@MBC maintained a near 100 % adsorption capacity for PFOA after 3 cycles of chemical regeneration; Fe@MBC also exhibited efficient removal for PFOA and other PFAS compounds at trace levels in the lake water and dairy effluent. (Guo et al., 2024)

5.3 Short-Chain PFAS Sorption Enhancement

Fe-doped (R-Fe) and Cu-doped biochars (R-Cu) were prepared using reed straw biochar (R); the PFBA and PFPeA sorption capacities of R-Fe were 25.81 and 43.59 mg g^{-1}, 1.65 and 1.55 times higher than those of R, respectively; ion-pair sorption, pore filling, electrostatic interaction between the Fe/Cu and cationic groups on biochar and the anionic groups of PFASs, and hydrophobic interaction were the underlying sorption mechanisms; the biochars presented high removal rates (>86 %) of multiple PFASs from synthetic wastewaters, including legacy and emerging PFASs of different chain lengths and with different functional groups. (Liu et al., 2024)

5.4 Nanocomposite and Advanced Materials

Biosolids-derived biochar achieved a CH_4 and CO_2 conversion of 50-70 % and 70-90 % at 900 °C with catalytic decomposition; high-quality carbon nanospheres (200-500 nm) and carbon nanofibres (10-100 nm) were formed on biochar surface; the CNM-loaded biochar was tested for PFAS adsorption from contaminated wastewater, achieving a removal efficiency of 79 % which was 10-60 % higher than using biochar and ilmenite alone. (Patel et al., 2023)

The biochar-enabled advanced reduction process (ARP) was developed for enhanced sorption (by biochar) and destruction of PFAS in water; compared to unmodified biochar, all modified biochars showed greater sorption efficiency, and the chi-BC (chitosan-modified biochar) performed the best for PFAS sorption; the chi-BC was then selected to facilitate reductive destruction and defluorination of PFAS in water by ARP in the UV-sulfite system; adding chi-BC in UV-sulfite ARP system significantly enhanced both degradation and defluorination efficiencies of PFAS (up to ~100% degradation and ~85% defluorination efficiencies). (Song et al., 2024).

6. Comparative Performance: Biochar vs. Conventional Adsorbents

6.1 Biochar vs. Activated Carbon

GAC exhibited high maximum Langmuir sorption capacity for both PFOS (123.5 μmol g−1) and PFOA (86.2 μmol g−1), which were 43% and 39.6% greater than biochar; however, all results indicate that adsorption technology is a feasible method to control the contamination of PFASs, and both GAC and biochar are effective adsorbents for PFASs removal from wastewater. (Zhang et al., 2019)

Of the 44 sorbents tested, PFASs sorbed best (mean >99.9 %) to activated carbons (granulated and pulverized); sorption of PFASs to magnesium chloride-fortified biochar, Moringa seed, and pyrolytic carbon waste was 17- to 25-fold higher than to sand; sorption generally increased with increasing perfluorocarbon chain length and based on functional group. (Sörengård et al., 2020)

6.2 Multi-Adsorbent Comparative Analysis

Adsorption of 44 PFAS was evaluated across four different adsorbent groups; activated carbon and biochar had the highest Kd for PFAS with ≥7C-F bonds; cyclodextrins and resins outperformed activated carbons and biochars for PFAS≤4C-F bonds; cyclodextrins outperform AC and BC for removing PFAS across varying mobilities from water, whereas AC and BC are superior for low mobility PFAS. (Saeidi et al., 2024)

7. Field Applications and Case Studies

7.1 Stormwater Treatment Systems

When stormwater biofilters are not saturated, per- and polyfluoroalkyl substances (PFASs) sorb to the air–water interface; the design of black carbon-amended stormwater biofilters for PFAS removal can be improved by preventing saturation. (Hawkins et al., 2024) 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; reactive soil mixes incorporating biochar, zeolite, and iron oxide as amendment media for enhanced PFAS adsorption in stormwater infiltration basins demonstrated 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. (Barua, 2024)

7.2 PFAS-Contaminated Soil Remediation

Laboratory-scale rainfall simulations evaluated PFAS losses in runoff and in leaching to groundwater (leachate) from AFFF-contaminated soils varying in texture, PFAS composition and concentration, and remediation treatment; leaching dominated PFAS losses in soils with lower

concentrations, while with higher soil PFAS concentrations, leachate volumes were negligible and runoff dominated losses; while concentrations of most PFASs declined significantly after the first rainfall event, desorption and transport in both runoff and leachates persisted over several rainfall events; sorption to activated carbon (AC) mostly occurred during, not prior to, rainfall events and 1% w/w AC substantially reduced losses in runoff and leachates from all soils. (Richardson et al., 2022)

7.3 Wastewater Treatment Applications

The adsorption performance of three common PFAS compounds (PFOA, PFOS and PFHxS) was assessed on two water treatment sludges (WTS) and two biochars; the results suggested that hydrophobicity of the sorbent and the chemistry of the coagulant were critical factors for understanding PFAS adsorption on WTS, while other factors such as concentration of aluminium and iron could not explain the observed trends; for biochar samples, the surface area and hydrophobicity are believed to be the main drivers in the different performances; adsorption from the solution containing multiple PFAS demonstrated comparable performance on overall adsorption, with PAC WTS performing better with the short-chain PFHxS than the biosolids biochar. (Nguyen et al., 2023)

8. Advanced Treatment Technologies and Integration

8.1 Treatment Train Approaches

Per- and polyfluoroalkyl substances (PFAS) are pollutants that have demonstrated a high level of environmental persistence and are very difficult to remediate; new research on PFAS remediation technologies has emerged to address the efficiency, costs, and other shortcomings of existing remediation methods; industry attention should focus on treatment train approaches to improve efficiency and reduce the cost of treatment. (Meegoda et al., 2020)

8.2 Combined Sorption and Destruction

A multiple lines of evidence approach were developed to assist regulators, funding agencies, and practitioners in evaluating PFAS treatment technology performance; each of three lines of evidence includes: (1) decrease in target PFAS concentrations; (2) PFAS treatment transformation products identification and quantification; and (3) treatment mechanism proposal consistent with previous studies and supported by data. (Wanzek et al., 2024)

8.3 PFAS Destruction Technologies

Per- and polyfluoroalkyl substances (PFASs) are a family of highly toxic emerging contaminants; the scientific community has been working on two fronts: (1) adapting already existing and effective technologies in destroying organic contaminants for PFAS remediation and (2) developing new technologies to remediate PFAS; the separation/removal of PFASs from other contaminants or media is followed by destruction; the separation technologies can remove PFASs from being in contact with humans; however, they remain in the environment and continue to pose

health risks; the destructive technologies can effectively destroy PFAS compounds and fully address society's urgent need to remediate this harmful family of chemical compounds. (Meegoda et al., 2022)

An innovative thermal degradation strategy was developed for treating per- and polyfluoroalkyl substance (PFAS)-containing solid materials that satisfies three criteria: the ability to achieve near-complete degradation of PFASs within a short timescale, nonselectivity, and low energy cost; subjecting PFASs to induction heating for a brief duration resulted in substantial degradation (>90%) of these compounds, including recalcitrant short-chain PFASs and perfluoroalkyl sulfonic acids; the rate-limiting step in PFAS thermal degradation is linked with phase transitions occurring on different time scales. (Xiao et al., 2023)

9. Biochar Properties and Contaminant Removal Efficiency

9.1 Predictive Modeling Approaches

Machine learning (ML) incorporating classical theoretical adsorption models was applied to build prediction models for adsorption kinetics rate and maximum adsorption capacity of emerging contaminants (ECs) on biochar; the surface chemistry, primarily led by ash content of biochar significantly influenced the adsorption kinetics rate, while surface porous structure of biochar showed a dominant role in predicting maximum adsorption capacity; an interactive platform was deployed for relevant scientists to predict adsorption parameters of new biochar for ECs. (Liu et al., 2024)

9.2 Sewage Sludge-Derived Biochar

Sewage sludge biochars (SSBCs) exhibited log-linear biochar-water distribution coefficients (log Kd) comparable to those previously reported for commercial activated carbons (e.g., 5.73 ± 0.02 for perfluorooctanoic acid at 1 µg/L); the strong sorption of PFCAs was attributed to the SSBCs relatively high pore volumes in the pore size range that can accommodate these compounds; sorption was attenuated by the presence of soil (by factors 3–10), by the presence of a mixture of PFCAs (by factors of 6–532) and by both together (by factors of 8–6581), indicating strongly competitive sorption between PFCA-congeners, and less severe sorption attenuation by soil organic matter. (Krahn et al., 2022)

10. Regulatory Framework and Standards

10.1 EPA Health Advisories and Drinking Water Standards

The US Environmental Protection Agency (USEPA) issued drinking water Health Advisories for PFOA and PFOS at 70 ng/L each and for the sum of the two; the need for an enforceable primary drinking water regulation under the Safe Drinking Water Act (SDWA) is currently being assessed; the USEPA faces stringent legal constraints and technical barriers to develop a primary drinking water regulation for PFOA and PFOS. (Pontius, 2019)

10.2 Global Regulatory Variation

Although USEPA recommends the 70 ng/L lifetime health advisory in drinking water for both PFOS and PFOA, which is similar to the Australian regulations, the German Ministry of Health proposed a health-based guidance of maximum of 300 ng/L for the combination of PFOA and PFOS; there are significant discrepancies among the US states where the water guideline levels for the different states ranged from 13 to 1000 ng L−1 for PFOA and/or PFOS. (Abunada et al., 2020)

10.3 European Regulatory Developments

Ultra-short PFAS (chain length C1–C3) have not been well studied; among others, trifluoroacetic acid (TFA) is present globally in concentrations that appear to be increasing; the substitution of individual PFAS recognized as hazardous by other possibly equally hazardous PFAS with virtually unknown chronic toxicity is not a solution; the only answer is a switch to fluorine-free alternatives for all applications in which PFAS are not essential. (Brunn et al., 2023)

10.4 Regulatory Policy on PFAS Remediation

The response by many states and the US Environmental Protection Agency (USEPA) to media exposure and public pressure related to PFAS contamination is to relatively quickly initiate programs to regulate PFAS sites; if PFAS are designated as hazardous substances at the federal level, there could be wide-reaching effects including listing of new Superfund sites solely for PFAS, application of stringent state standards, additional characterization and remediation at existing sites, reopening of closed sites, and cost renegotiation among responsible parties. (Simon et al., 2019)

11. Challenges and Limitations

11.1 Short-Chain PFAS Treatment Challenges

Short-chain perfluoroalkyl substance (PFAS) alternatives have been increasingly used in industrial and commercial products; short-chain PFASs remain persistent, potentially toxic, and extremely mobile, posing potential threats to human health because of their widespread pollution and accumulation in the water cycle; adsorption was the most widely used and effective method for eliminating short-chain PFASs with a broad range of concentrations and meeting low-carbon policy, although the adsorbent regeneration was undesirable. (Liu et al., 2022)

11.2 PFAS Precursor and Transformation Product Formation

In biodegradation of perfluorooctane sulfonic acid (PFOS), firstly C−S bond cleavage occurs which is followed by hydroxylation, decarboxylation and defluorination reactions to form perfluoroheptanoic acid; in hydrothermal liquefaction (HTL), PFOS degradation is carried through OH−catalyzed series of nucleophilic substitution and decarboxylation reactions; in thermal PFOS degradation involves a three-step random-chain scission pathway. (Kumar et al., 2023)

11.3 Pyrolysis of PFAS-Contaminated Biosolids

Pyrolysis can remove PFAS from biosolids; however, it has been shown to produce PFAS that reside in py-liquid, and the fate in py-gas remains a knowledge gap; more research is needed to help close the PFAS and fluorine mass balance through pyrolysis influent and effluent products because pyrolysis alone does not destroy all PFAS; pyrolysis has both defined benefits (solids reduction, PFAS removal from biosolids, and biochar production) as well as remaining questions (the fate of PFAS in py-gas and py-liquid, mass balance on nutrients, and py-liquid handling options). (McNamara et al., 2023)

11.4 Adsorbent Regeneration and Reusability

A critical review on PFAS removal from water reveals that the efficiency of all techniques to eradicate short-chain PFAS is comparatively lower compared to long-chain PFAS; destruction techniques are the most efficient but have some drawbacks, including the formation of PFAS precursors and high operational costs; combined methods will be required to effectively remediate PFAS-contaminated water. (Dickman & Aga, 2022)

12. Future Regulatory Implications

12.1 Emerging PFAS Regulations and Control Strategies

The consensus of removing per- and polyfluoroalkyl substances (PFAS) from the environment is widely recognized and enlightened by the near-zero standards released from the U.S. Environmental Protection Agency in 2023; the only way to achieve the goal of zero fluoro-pollution is to fully defluorinate or mineralize PFAS, but current technologies only partially defluorinate a limited number of PFAS, which can lead to the creation of potentially more toxic short-chain intermediates; technological gaps in the aspects of water matrix effects, pilot tests, and cost analysis also limit the application and comparison of different treatment technologies. (Juve et al., 2023)

12.2 Sustainability and Carbon Sequestration

Biochar was usually prepared from biomass and solid wastes such as agricultural and forestry waste, sludge, livestock, and poultry manure; the wide application of biochar is due to its abilities to remove pollutants, remediate contaminated soil, and reduce greenhouse gas emissions. (Yang et al., 2019)

12.3 Comprehensive Treatment Framework

Treatment methods are needed to effectively sequester or destroy a variety of PFASs from groundwater, drinking water, and wastewater; due to the stability of PFASs, a combination of multiple treatment technologies will likely be required to effectively address real-world complexities of PFAS mixtures and cocontaminants present in environmental matrices. (Merino et al., 2016).

13. Research Gaps and Future Directions

13.1 Mechanistic Understanding

Despite advances in biochar research, significant knowledge gaps remain regarding the fundamental mechanisms governing PFAS-biochar interactions, particularly for emerging short-chain and ultra-short-chain PFAS. It is essential to adjust the physical and chemical properties of biochar due to its low concentration and distinct chemical composition; most notably, char's high surface area and C and N content are the primary controlling elements during PFAS adsorption. (Mainali, 2024) Future research must employ advanced spectroscopic and computational techniques to elucidate molecular-level interactions.

13.2 Field-Scale Demonstration and Optimization

Research on PFAS chemicals is extensive and covers all aspects, including analytical quantification, determination of properties, toxicology, ex situ treatment, and in situ remediation; although there are many unknowns about PFAS chemicals, degradation pathways, reaction rates, etc., many different sorption, oxidation, reduction, biological, and innovative treatment approaches are being developed; sorption with activated carbon is currently the only fully available in situ treatment technology for PFAS-impacted groundwater; given the wide array of PFAS chemicals and transformation products, remediation may need multi-step treatment trains to fully address the PFAS contamination. (Johnson et al., 2023)

13.3 Scaling and Economic Feasibility

The transition from laboratory to field-scale applications remains a critical challenge. Despite the preparation methods and properties of biochar have been studied, its large-scale application in industrial wastewater treatment has not yet been fully understood and clarified; biochar is a material with good application potential for industrial wastewater treatment, with its high specific surface area and rich surface functional groups giving it good adsorption capacity for various pollutants in industrial wastewater. (Xu, 2023)

13.4 Leaching Assessment and Long-Term Fate

Understanding PFAS leaching is crucial for assessing risks associated with leaving impacted material in place, reuse, or disposal; however, there is limited guidance on laboratory methods to measure extent and rate of leaching; most methods use saturated conditions that do not account for the possible influence of air–water interface accumulation and wetting–drying cycles on leaching; a notable gap is the scarcity of data benchmarking laboratory-leached concentrations with real-world PFAS concentrations. (Navarro et al., 2024)

14. Synthesis and Conclusions

Biochar represents a promising, sustainable, and cost-effective technology for PFAS removal from industrial stormwater and wastewater. The multifaceted mechanisms underlying PFAS adsorption to biochar—encompassing electrostatic interactions, hydrogen bonding, and hydrophobic

partitioning—enable removal of diverse PFAS classes with varying chain lengths and functional groups. Strategic modification of biochar through metal/metal oxide incorporation, acid-base treatment, and nanocomposite development has significantly enhanced PFAS sorption capacity and selectivity, particularly for challenging short-chain compounds.

Field applications of biochar-amended systems in stormwater infiltration, soil remediation, and wastewater treatment have demonstrated practical viability and sustained contaminant reduction. However, numerous challenges persist: (1) incomplete removal of short-chain PFAS and emerging alternatives; (2) formation of potentially toxic transformation products during thermal treatment; (3) limited regeneration and reusability of spent biochar; (4) scaling barriers for commercial implementation; and (5) knowledge gaps regarding long-term environmental fate and leachability.

The evolving global regulatory landscape, characterized by increasingly stringent drinking water standards and near-zero cleanup targets, necessitates a paradigm shift toward integrated treatment train approaches combining sorption, destruction, and transformation product management. Future success in PFAS remediation will require synergistic development of: (1) advanced modified biochar formulations tailored to specific PFAS classes and contamination scenarios; (2) predictive modeling frameworks to optimize material design and system performance; (3) comprehensive field demonstrations bridging laboratory efficacy to real-world conditions; (4) circular economy strategies for biochar regeneration and valorization; and (5) policy frameworks supporting sustainable alternatives to fluorinated chemicals.

Biochar technologies, when integrated within comprehensive multi-barrier systems and supported by rigorous field validation and regulatory harmonization, can play a pivotal role in mitigating the pervasive PFAS contamination crisis and protecting human health and ecosystem integrity globally.

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