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Review

# Biomass-Based adsorbents for PFAS Remediation: From functionalization to disposal

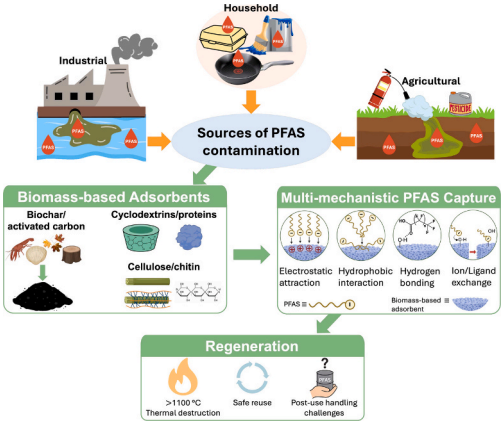
Neda Arabzadeh Nosratabad [a,1], Qiangu Yan [b,1], Zhiyong Cai [b,*], Caixia Wan [a,*]

[a] Department of Chemical and Biomedical Engineering, University of Missouri, 416 S 6th Street, Lafferre Hall, Columbia, MO 65201, United States
[b] Forest Products Laboratory, USDA Forest Service, One Gifford Pinchot Drive, Madison, WI 53726-2398, United States

## HIGHLIGHTS

- Biomass-derived adsorbents enabling greener PFAS remediation and reuse.
- Adsorption capacities vary widely, reaching > 8000 mg/g for advanced materials.
- Major PFAS–biomass adsorption mechanisms: electrostatic, hydrophobic, H-bonding.
- Surface modification to boost PFAS affinity, selectivity, and adsorption kinetics.
- Practical use requires scalable synthesis and stable performance in real waters.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are persistent synthetic pollutants that resist degradation due to strong carbon–fluorine bonds, posing risks to ecosystems and human health through bioaccumulation, toxicity, and carcinogenicity. Adsorption has emerged as a cost-effective remediation approach, with biomass-based adsorbents offering sustainable alternatives to conventional materials due to their low cost and tunable surface chemistry. Reported adsorption capacities vary widely depending on material design. This review critically examines recent advances in the functionalization and engineering of biomass-derived adsorbents to enhance PFAS binding efficiency, selectivity, and reusability. Key mechanisms, surface modification strategies, and challenges in regeneration and secondary pollution are discussed. Overall, this review identifies critical research gaps and provides guidance for developing scalable, efficient, and sustainable PFAS remediation technologies.

* Corresponding authors.
*E-mail addresses:* zhiyong.cai@usda.gov (Z. Cai), wanca@missouri.edu (C. Wan).
[1] These authors contributed equally.

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## 1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a large class of synthetic fluorinated compounds containing partially fluorinated (polyfluoroalkyl) or fully fluorinated (perfluoroalkyl) carbon chains (Buck et al., 2011). These molecules typically consist of a hydrophobic fluorinated carbon chain and a hydrophilic functional group, such as sulfonate ($-SO_3^-$), carboxylate ($-COO^-$), and phosphate ($PO_4^-$). Their exceptionally strong carbon–fluorine (C–F) bonds, with bond energies of approximately 544 kJ/mol, impart extraordinary resistance to thermal, chemical, and biological degradation (Vakili et al., 2024; Yin & Villagrán, 2022). As a result, PFAS persist in the environment for extended periods and are commonly referred to as "forever chemicals." Representative chemical structures of widely studied PFAS are shown in Fig. 1 (Y. Liu et al., 2022). PFAS are commonly classified as short- or long-chain species based on fluorocarbon chain length, with long-chain PFAS exhibiting greater bioaccumulation and environmental persistence (Qi, Li, Wu, Lin, & Chen, 2022). Since their introduction in the 1940s (Prevedouros, Cousins, Buck, & Korzeniowski, 2006), PFAS have been widely used in firefighting foams, non-stick cookware, waterproof textiles, food packaging, and stain-resistant coatings due to their hydrophobic, oleophobic, and chemically inert properties (Leung, Wanninayake, Chen, Nguyen, & Li, 2023; Pauletto & Bandosz, 2022). Decades of extensive use and inadequate waste management have led to widespread contamination of water, soil, and biota, with PFAS now frequently detected in environmental matrices and human blood (Dimitrakopoulou et al., 2024). These substances are associated with severe health impacts, such as immune suppression, developmental setbacks, reproductive issues, thyroid and liver toxicity, and a heightened risk of cancer (Fenton et al., 2021). PFAS detection in drinking water has raised serious concerns due to ingestion risks, leading to stricter global regulatory limits (Chambial, Thakur, Kushawaha, & Kumar, 2025). In May 2025, the U.S. Environmental Protection Agency (EPA) established its first legally enforceable National Primary Drinking Water Regulation (NPDWR), setting maximum contaminant levels of 4 ppt for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), 10 ppt for perfluorohexane sulfonic acid (PFHxS), perfluorononanoic acid (PFNA), and hexafluoropropylene oxide dimer acid (HFPO-DA), and applying a hazard-index approach for PFAS mixtures (Agency, 2025). These regulations have intensified the demand for effective and scalable PFAS removal technologies. Although some advanced oxidation processes, membrane filtration, and biodegradation techniques have shown promise, their widespread application is often limited by high energy demands, operational complexity, and cost (Tushar, Pushan, Aich, & Rowles, 2024). Among available approaches, adsorption-based techniques are widely applied due to their high efficiency, affordability, and operational simplicity, using materials such as activated carbon, ion-exchange resins, and engineered biochar (Z. Chen, Zhao, Wei, & Shen, 2025; Loganathan, Kandasamy, Ratnaweera, & Vigneswaran, 2024; Malouchi et al., 2024; D. Q. Zhang, Zhang, & Liang, 2019). However, the management of spent adsorbents remains a critical challenge. Conventional disposal routes such as landfilling or incineration may lead to secondary pollution, including PFAS release, formation of toxic byproducts, and greenhouse gas emissions (Soker et al., 2025; Tshangana et al., 2025; Vakili et al., 2024). To enhance the sustainability of adsorption-based PFAS treatment, increasing attention has focused on adsorbent regeneration and reuse. An effective regeneration strategy should promote PFAS desorption while preserving the material's structural integrity and adsorption capacity over multiple cycles.

Recently, biomass-derived adsorbents have gained interest as greener alternatives to conventional synthetic materials due to their low cost, renewable origin, and tunable surface chemistry (Li et al., 2021). However, several challenges remain in this area, particularly related to performance stability during repeated regeneration cycles. Enhancing

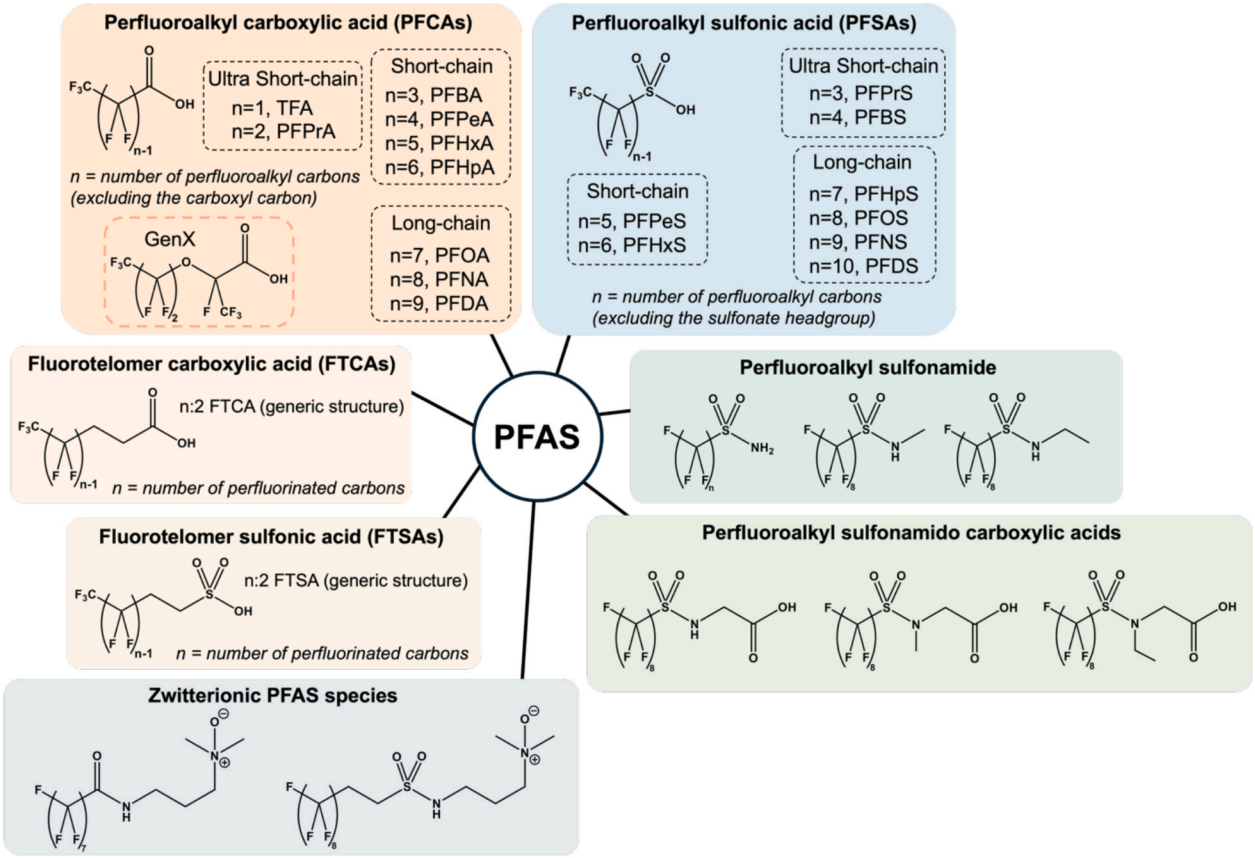


**Fig. 1.** Chemical structures of common PFAS Compounds.

PFAS desorption efficiency while minimizing material degradation under optimized regeneration conditions remains a key concern. Furthermore, chemical changes such as oxidation, loss of surface functional groups, backbone degradation of biopolymers, and irreversible site modification during regeneration may limit the long-term applicability of biomass-based adsorbents, making it difficult to maintain their structural integrity and adsorption performance over repeated use (Hashem & Farag, 2025; Sonmez Baghirzade et al., 2021). Current regeneration technologies, such as chemical washing, thermal treatment, and advanced oxidation, have demonstrated varying degrees of success (Vakili et al., 2024). However, regeneration outcomes remain highly material- and method-dependent, and the mechanisms governing PFAS desorption and adsorbent degradation during repeated use are not yet fully understood.

This review critically examines recent advances in biomass-derived adsorbents for PFAS removal from water systems, with emphasis on adsorption mechanisms, surface functionalization strategies, and regeneration performance. In addition, the environmental and practical challenges associated with post-use handling and long-term applicability of PFAS-laden biomass materials are also discussed. By synthesizing recent findings, this review aims to clarify current limitations and highlight future research directions toward sustainable and effective PFAS remediation using biomass-based adsorbents.

## 2. Biomass-based adsorbents for PFAS removal

A wide range of adsorbents has been investigated for PFAS removal from contaminated environments (Dey, Shafi, Chowdhury, Dubey, & Sen, 2024). Among these, biomass-based materials have attracted increasing attention due to their abundance, cost-effectiveness, and sustainability. Biomass-derived adsorbents, including biochar, lignocellulosic materials, and biopolymer-based sorbents, offer a promising alternative to conventional adsorbents such as ion-exchange resins. Their porous structures, tunable surface chemistry, and diverse functional groups enable PFAS adsorption through multiple mechanisms, including hydrophobic interactions, electrostatic attraction, ligand exchange, van der Waals forces, π–π interactions, pore diffusion, and self-aggregation phenomena (e.g., micelle or hemimicelle formation) (Gagliano, Sgroi, Falciglia, Vagliasindi, & Roccaro, 2020; Loganathan et al., 2024; Zhang et al., 2023). Unlike ion-exchange resins, which rely primarily on reversible ion-exchange, biomass-based adsorbents exploit intrinsic structural and chemical features, providing a more sustainable and economical PFAS removal strategy. This section categorizes biomass-derived adsorbents into four groups: (1) carbon-based adsorbents, (2) polysaccharide-based adsorbents, (3) MOF/COF biocomposites, and (4) other biomass-derived materials.

### 2.1. Carbon-based adsorbents

Activated carbon (AC) and biochar are widely studied for PFAS removal due to high surface area and porous structures. AC is cost-effective, broadly used in water treatment, and produced by physical or chemical activation of carbon-rich precursors at high temperature. Biomass-derived AC offers a renewable, tunable alternative with strong adsorption capacity (Joseph et al., 2021; Riegel, Haist-Gulde, & Sacher, 2023; Zhi & Liu, 2016). Materials such as powdered (PAC) and granular activated carbon (GAC) exploit hydrophobic interactions between PFAS and their nonpolar surfaces, making them particularly effective for long-chain PFAS (S. Deng et al., 2015; Pauletto & Bandosz, 2022). Biomass-derived adsorbents exemplified by bamboo-derived AC (BAC) have shown remarkable potential for PFAS removal (Du et al., 2015). Compared to non-biomass-based microporous AC, BAC exhibited a significantly higher adsorption capacity for PFOA, reaching 1.15 mmol/g at pH 5, whereas microporous AC demonstrated a lower adsorption capacity (0.470 mmol/g) (Du et al., 2015; B. Wang et al., 2016). These results underscore the potential of biomass-derived ACs to achieve better PFAS removal efficiency compared to non-biomass-derived ACs, emphasizing the importance of precursor material selection in developing effective adsorbents for PFAS remediation.

Biochar has emerged as a highly promising, low-cost biomass-based adsorbent with tunable surface properties and a wide range of feedstock availability. While biochar shares certain similarities with AC, including its porous structure and functional surface chemistry, biochar is usually produced at much lower temperatures, which favors higher yield and a higher specific surface area (Nosratabad, Yan, Cai, & Wan, 2024; Vakili et al., 2024). Nevertheless, recent advancements in biochar engineering, such as functionalizing biochar with amines, metals, or hybrid composites, have significantly enhanced its PFAS adsorption capacity and selectivity, positioning it as a promising alternative to conventional sorbents (A. Kumar, Shaikh, Maqsood, Parikh, & Biswas, 2025; M. Zhang et al., 2020). Biochar is derived from biomass via pyrolysis, producing a carbon-rich porous material (Dey et al., 2024). Various biomass sources have been explored for biochar production, including coconut shells, sawdust, plant fibers, waste wood chips, corn straw, chicken manure, and even sewage sludge (Hassan, Liu, Naidu, Du, & Qi, 2020; Niu et al., 2020; Zhang, He, Wang, Zhang, & Liang, 2021; Zhang et al., 2023; Zhou et al., 2021). The ability to utilize agricultural and organic waste for biochar production not only provides a sustainable disposal solution but also enhances the circular economy by converting waste into valuable adsorbents. Several studies have demonstrated the high PFAS adsorption efficiency of biochar (Krahn et al., 2023; N. Liu, Wu, Lyu, & Li, 2021; Sørmo et al., 2021). For instance, Wang et al. investigated the effects of pyrolysis temperature and thermal post-treatment on biochar's performance in PFAS removal (Wang, Alinezhad, Sun, Xiao, & Pignatello, 2023). Biochar produced from softwood and hardwood shavings at pyrolysis temperatures of 300–600 °C exhibited increased surface area and porosity after post-pyrolysis air oxidation, thereby improving its suitability for PFAS adsorption. This treatment increased PFAS sorption affinity, as quantified by the solid–water distribution coefficient ($K_d$), by up to three orders of magnitude for short-chain PFAS (e.g., perfluorobutanoic acid (PFBA) and PFPeA), with $K_d$ values rising from below the detection limit to $\geq 10^4$-$10^5$ L/kg. Post-regeneration sorption tests showed that the reactivated biochar consistently outperformed untreated biochar and, for certain PFAS (i.e., PFBA and PFPeA), approached the $K_d$ values reported for commercial GAC.

Although biochar is considered a cost-effective and eco-friendly adsorbent for PFAS removal, its efficiency is hindered by several limitations (Behnami et al., 2024). Short-chain PFAS (e.g., PFBS and PFBA) are highly water-soluble, limiting their adsorption onto hydrophobic carbon surfaces. The predominantly negatively charged biochar surface at circumneutral pH further reduces electrostatic affinity for anionic PFAS (Vu & Wu, 2022; D. Q. Zhang et al., 2019). Additionally, pristine biochar often lacks sufficient functional groups for selective adsorption, and its regeneration remains costly and inefficient (Deng et al., 2023; Shaikh, Sarkar, & Nawaz, 2023). To address these limitations, engineered biochar composites incorporating polymers, carbon nanomaterials, metallic nanoparticles, or surfactants have been developed to enhance surface properties and improve PFAS-binding capacity (Deng et al., 2023; Hassan et al., 2022; Patel et al., 2023; Shaikh et al., 2023; Wu, Qi, & Chen, 2022; Yea et al., 2022; Yu et al., 2023; Zoroufchi Benis, Shakouri, McPhedran, & Soltan, 2021). For example, ferric chloride ($FeCl_3$)-modified biochar derived from softwood, hardwood, and biosolids introduced cationic sites and improved porosity (Wu et al., 2022). These cationic modifications enhanced the surface properties and strengthened electrostatic interactions between the anionic PFOA and the biochar surface. The modified biosolid-derived biochar achieved a PFOA adsorption capacity of 469.65 μmol/g, outperforming unmodified biochar and commercial GAC. Surfactant modification can also enhance the surface functional groups of biochar, thereby increasing its adsorption capacity for PFAS. For instance, modifying Karanja shell biochar with cetyltrimethylammonium bromide (CTAB) increased its PFOA adsorption capacity from 157.1 to 455.8 mg/g and retained

approximately 90% removal efficiency in the presence of co-contaminants such as humic substances, clay, anions, and cations. This enhancement was attributed to the introduction of quaternary ammonium functional groups and the long hydrophobic alkyl chain of CTAB, which strengthened electrostatic and hydrophobic interactions with PFAS (Shaikh et al., 2023).

Table 1 summarizes the various carbon-based adsorbents discussed in this section, including biomass sources, modification strategies, adsorption capacities, and removal mechanisms. From an application perspective, the materials summarized in Table 1 highlight clear distinctions between laboratory performance and real-world implementation. Currently, commercial PFAS treatment is dominated by established sorbents such as GAC and ion-exchange resins, which are widely used in drinking water systems (Ramos & Ashworth, 2024). Bench- and pilot-scale studies show that GAC preferentially removes long-chain PFAS, while removal of short-chain PFAS is less effective. Earlier breakthrough of short-chain PFAS (e.g., PFBA) has been observed in GAC column systems, highlighting a key limitation of carbon-based adsorption treatment (Appleman et al., 2014; Inyang & Dickenson, 2017). In contrast, most biochar-based PFAS adsorbents summarized in Table 1 remain at the laboratory or early pilot scale. Recent reviews emphasize that biochar performance varies greatly depending on feedstock, surface chemistry, and modification strategy, and that adsorption is also influenced by PFAS chain length and functional groups (Meservey et al., 2024). Although engineered biochar shows improved performance, current studies remain in an early stage of development, with limited systematic investigation and practical application (Teng, Zhao, Xia, Wu, & Wang, 2024).

### 2.2. Polysaccharides-/derivatives-based adsorbents

Chitin, a natural polymer of *N*-acetylglucosamine, is the second most abundant polysaccharide (next to cellulose). It is primarily obtained from marine crustaceans such as shrimp and crab shells and is also found in fungi and insect exoskeletons. Its derivative, chitosan, is produced by partial deacetylation, which exposes amine ($–NH_2$) groups, enhancing reactivity and solubility in acidic solutions (Rinaudo, 2006). Leveraging these functional groups, chitosan is widely applied as a bio-adsorbent for

**Table 1**
Carbon-based adsorbents derived from various biomass sources used for PFAS removal.

| Carbonaceous Adsorbents | Biomass Source/ Precursor | Modification/ Functionalization | Matrix & Conditions | Adsorption Capacity (mg/g) | Mechanism | Reference |
|---|---|---|---|---|---|---|
| Granular activated carbon | Bamboo | KOH activation | DI water; pH 5.0; 25 °C | PFOS = 1248 mg/g PFOA = 501 mg/g | Hydrophobic and electrostatic interactions | (Deng et al., 2015) |
| Wood-based activated carbon (BioNC and WVB) | – | Ammonia gas treatment | 10 mM NaCl in DI water; pH not specified; 25 °C | – | Surface basicity | (Zhi & Liu, 2016) |
| Bamboo-derived activated carbon | Bamboo | KOH activation | Actual PFOS washing wastewater (high ionic strength); pH 4.0; 25 °C | PFOA = 426 mg/g | Hydrophobic interactions (dominant at pH > 5), Electrostatic attraction (at low pH) | (Du et al., 2015) |
| Biochar | Softwood shavings | Coated by poly (dimethyldiallylammonium) chloride (pDADMAC) | 1 mM NaCl, 1 mM $NaHCO_3$ buffer; pH 7.4; 22 °C | – | Pore reaming, Hydrophobic interactions, Ion-pair sorption | (Wang, Alinezhad, Nason, Xiao, & Pignatello, 2023) |
| Biochar | Softwood and maple shavings | Post-pyrolysis air oxidized | Ultrapure water with 1 mM NaCl, 1 mM $NaHCO_3$; pH 7.4; 22 °C | – | Hydrophobic interactions, Dispersion forces, Pore reaming | (Wang, Alinezhad, Sun, et al., 2023) |
| Activated biochar | Waste timber | Steam ($H_2O$) or carbon dioxide ($CO_2$) activation | Soil leaching test with ultrapure water (18 MΩ); Soil Leachate pH: 7–8 (Low-TOC soil); 20 °C | – | Hydrophobic interactions, Electrostatic interactions, Pore size effects | (Sørmo et al., 2021) |
| Biochar | Reed straw | – | Ultrapure water; pH 3–12; 24 ± 2 °C | PFOS = 34.6 mg/g | Hydrophobic interactions and mesoporous structure | (Liu et al., 2021) |
| Biochar | Sewage sludge | Ball milling | Ultrapure water; pH not specified; 23 °C | – | Hydrophobic interactions (chain-length dependent) | (Krahn et al., 2023) |
| Activated biochar-polyaniline hybrid composite | Bamboo | Chemical activation ($HNO_3/H_2SO_4$) */in situ* polymerization of polyaniline | Ultrapure water; pH 3.0; 25 °C | PFOA = 264.6 mg/g PFOS = 349.5 mg/g PFHxS = 327.6 mg/g | Electrostatic Attraction, Hydrogen bonding, Hydrophobic interactions, Surface complexation | (Yea et al., 2022) |
| Hybrid composite (MOF@AC) | Bamboo (Activated Carbon nanopowder) | In situ growth of MOF on activated carbon | Aqueous solution; pH 4.0; 25 °C | PFOS = 25.7 mg/g | Electrostatic and hydrophobic interactions | (Pala et al., 2023) |
| Biochar | Dried biosolids from a wastewater treatment plant | In situ carbon nanomaterials growth via chemical vapor deposition at 900 °C | PFAS-contaminated trade wastewater; pH not specified; ambient temperature | – | Hydrophobic and electrostatic interactions | (Patel et al., 2023) |
| Engineered biochar | Switchgrass, Water oak leaves, Biosolid | Fe-impregnated biochar/Carbon nanotubes-coated biochar | DI water; pH 5.0; 30 °C | PFOA = 194.5 mg/g | Electrostatic interaction, Hydrogen bonding, Hydrophobic interactions | (Wu et al., 2022) |
| Engineered biochar | Waste Karanja shells | Cetyltrimethylammonium bromide (CTAB) | DI water; pH 5.0; ambient temperature | PFOA = 455.8 mg/g | Hydrophobic and electrostatic interactions | (Shaikh et al., 2023) |

heavy metals, dyes, and PFAS from contaminated water (Bhatnagar & Sillanpää, 2009; Liang et al., 2018). Unlike other adsorbents, chitosan can efficiently bind anionic pollutants via electrostatic interactions, hydrogen bonding, and chelation, making it a promising material for water remediation without requiring extensive modifications (Cagnetta, Yin, Qiu, & Vakili, 2024; Elanchezhiyan, Preethi, Rathinam, Njaramba, & Park, 2021; Yu, Deng, & Yu, 2008; Zhang, Deng, Yu, & Huang, 2011; Zhang et al., 2024). For example, magnetic chitosan and chitin cryogels achieved a PFOA adsorption capacity of 451 mg/g. The incorporated $Fe_3O_4$ nanoparticles facilitated magnetic separation, improving recyclability, while life cycle assessments indicated a low environmental impact (García-Castrillo et al., 2024). Another study developed polyethyleneimine (PEI)-grafted chitosan beads (GCBs). PEI grafting introduced additional amine groups, enhancing electrostatic interactions with anionic PFAS. The GCBs demonstrated a tenfold increase in adsorption capacity compared to unmodified chitosan, with log $K_d$ values ranging from 1.5 to 2.5 for both long- and short-chain PFAS. They also showed high selectivity in complex leachate environments and sustained their performance through multiple ethanol-based regeneration cycles (Shahrokhi & Park, 2024).

Cellulose, a linear polysaccharide composed of glucose units, is one of the most abundant and low-cost natural polymers, widely explored for environmental remediation (Rojas, 2016). Although direct studies on cellulose-based adsorbents for PFAS removal are limited, chemical modification can significantly enhance their performance by introducing effective binding sites through grafting or surface functionalization (Gomri, Benkhaled, Cretin, & Semsarilar, 2024). For instance, poly(ethylenimine)-functionalized microcrystalline cellulose (PEI-f-CMC) demonstrated rapid, near-instant removal of PFOA (up to 85% at pH 4.4) at environmentally relevant concentrations (<1000 ng/L), outperforming GAC in both kinetics and capacity. Despite a low surface area (7.8 $m^2$/g), it achieved a high adsorption capacity ($q_{max} = 2.32$ mg/g) and maintained consistent performance over eight adsorption–desorption cycles. The optimal performance was attributed to the presence of amine groups on the PEI, which promoted electrostatic attraction with anionic PFAS (Ateia et al., 2018). In addition to PEI-functionalized cellulose, other modifications have shown strong potential for PFAS remediation. In another approach, quaternary ammonium groups were grafted onto *Phormium tenax* (flax) cellulose fibers via atom transfer radical polymerization. These cationic fibers removed 86% of PFBS and 57% of PFBA (initial concentration 100 μg/L, dose 50 mg/L) within 24 h, matching the performance of a strong-base ion-exchange resin and outperforming GAC. The maximum PFBS capacity was 43 mg/g, and regeneration recovered over 78% of PFBS and 97% of PFBA (Data et al., 2025). Thanks to its renewable cellulose base, permanent cationic sites, and stability in pH 5–7, this quaternary ammonium-grafted flax fiber offers a promising, eco-friendly sorbent for efficient and sustainable removal of short-chain PFAS from water.

Cyclodextrins (CDs) are a class of cyclic oligosaccharides derived from starch (α-, β-, and γ-CD with 6, 7, and 8 glucose units, respectively) and possess a hydrophobic cavity and hydrophilic outer surface, enabling them to form inclusion complexes with hydrophobic molecules like PFAS (Schneiderman & Stalcup, 2000; Wacławek et al., 2022). Unmodified cyclodextrin polymers (CDPs) typically exhibit moderate affinity for PFAS, necessitating structural modifications to enhance their adsorption performance (Ling et al., 2017; Xiao et al., 2017). In a study by Yang et al., a novel amine-functionalized β-CD polymer (CDP1) achieved a 100-fold higher affinity and double the adsorption capacity for PFOA and hexafluoropropylene oxide (GenX) compared to previous β-CD materials, leveraging synergistic electrostatic and host–guest interactions (Yang, Ching, Easler, Helbling, & Dichtel, 2020). A recent study synthesized three β-CD derivatives (β-CD-*EPI*, β-CD-HDI, and β-CD-Cl). β-CD-*EPI*, crosslinked with epichlorohydrin, primarily relied on host–guest interactions, whereas β-CD-HDI, incorporating hexamethylene diisocyanate, enhanced hydrophobic and electrostatic binding. The chlorine-functionalized β-CD-Cl exhibited the highest adsorption efficiency, highlighting how targeted functionalization can optimize CD-based adsorbents for PFAS remediation (Abaie et al., 2024). Table 2 outlines polysaccharide-based and derivative adsorbents evaluated for PFAS removal, detailing their biomass sources, modification methods, adsorption performance, and underlying removal mechanisms.

### 2.3. Porous framework adsorbents derived from biomass – COFs and MOFs

Covalent organic frameworks (COFs) and metal–organic frameworks (MOFs) are nanostructured porous materials characterized by precisely controlled compositions and tunable porosity. They often demonstrate exceptionally high surface areas, sometimes reaching several thousand $m^2$/g, and have shown significant potential for PFAS adsorption (Chung et al., 2023; Karbassiyazdi et al., 2023; Li et al., 2023; Pauletto & Bandosz, 2022). A key difference is that MOFs contain metal ions, which facilitate Lewis acid-base interactions, as well as hydrophobic, electrostatic, and hydrogen bonding with PFAS. This section emphasizes COFs and MOFs made from renewable sources such as lignocellulose, chitosan, and tannic acid, highlighting them as sustainable, low-cost alternatives to purely synthetic frameworks.

For instance, a chitosan-coated fluoro-functionalized COF (chitosan/F-COF) showed exceptional adsorption abilities, with capacities of 8307.1 mg/g for PFOS, 6177.1 mg/g for PFOA, and 4603.3 mg/g for GenX. These results surpass many traditional adsorbents. Additionally, it achieved removal efficiencies over 88.4% in real-world water samples, underscoring its promise as a recyclable, biomass-based adsorbent (He, Yang, Hou, Luan, & Deng, 2022). In a study by Pala et al., a hybrid MOF-biomass adsorbent was developed by integrating bamboo-derived AC into a MIL-101(Cr) framework. This MIL-101(Cr)@AC composite combines the high capacity of MOFs with the durability and reusability of biomass-derived AC, resulting in 80% PFOS removal within 2 h. The hybrid structure enhanced adsorption kinetics and, after multiple regeneration cycles, still retained over 70% efficiency, highlighting its potential as a sustainable solution for PFAS cleanup (Pala, Le, Kasula, & Rabbani Esfahani, 2023).

### 2.4. Other biomass-based adsorbents

Beyond the categories above, various biomass-based adsorbents have been explored for PFAS removal and can be broadly classified as protein- or lignocellulose-based materials. Protein-based adsorbents derived from agricultural and food industry byproducts are promising due to their inherent surface functionalities, hydrophobic domains, and electrostatic interaction sites. Studies have shown that proteins like bovine serum albumin (BSA), lysozyme, and hemp protein can bind diverse PFAS in both ultrapure and natural waters (Malomo & Aluko, 2015; Mantripragada, Dong, & Zhang, 2023; Peydayesh & Mezzenga, 2021; Turner, Sloan, & Currell, 2019; Vinayagam et al., 2022). For example, Hernandez et al. reported that BSA and lysozyme removed nearly 99% of several PFAS (PFOA, HFPO-DA, PFBS, PFBA) at environmentally relevant concentrations (i.e., 250 ppb). BSA performed consistently well across varying pH and high ionic strength, while lysozyme showed specific advantages for short-chain PFAS, such as PFBA. The study confirmed that electrostatic and hydrophobic interactions, governed by protein charge and structure, are key mechanisms of adsorption (Hernandez et al., 2022).

Lignocellulosic biomass, comprising cellulose, hemicellulose, and lignin, offers a low-cost, hierarchical structure with functional groups that promote PFAS adsorption. A notable example derived from lignocellulosic components is the Renewable Artificial Plant for *in situ* Microbial Environmental Remediation (RAPIMER), fabricated from cornstover–derived cellulose nanofibrils and PEI–modified lignin. This 3D nano-framework is amphiphilic, combining negatively charged hydrophilic cellulose with positively charged hydrophobic lignin-PEI to enhance both electrostatic binding to PFAS headgroups and

**Table 2**
Overview of polysaccharides-/their derivatives-based adsorbents for PFAS adsorption.

| Polysaccharides-/ their derivatives Adsorbents | Biomass Source/ Precursor | Modification/ Functionalization | Matrix & Conditions | Adsorption Capacity (mg/g) | Mechanism | Reference |
|---|---|---|---|---|---|---|
| Chitosan cryogels | Chitosan | Magnetic functionalization with $Fe_3O_4$ nanoparticles | Aqueous solution; pH not specified; ambient temperature | PFOA = 451.4 mg/g PFDA = 312.3 mg/g | Electrostatic interactions, Hydrogen bonding, Hydrophobic interactions (for fluorinated tail) | (García-Castrillo et al., 2024) |
| Chitosan-coated COF composite | Chitosan | COF embedded in chitosan via dissolution–evaporation | Aqueous solution; pH 5.0 ± 0.1; 25 °C | PFOA = 2.8 mg/g | Electrostatic interactions, Hydrogen bonding, Van der Waals forces | (Zhang et al., 2024) |
| Grafted crushed chitosan beads | Chitosan from crustacean shells/ fungi | Polyethyleneimine grafted onto chitosan beads using epichlorohydrin (ECH) crosslinker | DI water; pH 7.0; 22 ± 2 °C | PFOA = 230.1 mg/g PFOS = 269.2 mg/g PFBA = 305.8 mg/g PFBS = 260.2 mg/g | Electrostatic attractions, Hydrogen bonding, Hydrophobic interactions | (Shahrokhi & Park, 2024) |
| Chitosan beads −based Molecularly Imprinted Polymer (MIP) | Chitosan | MIP with PFOS template; ECH crosslinked | Aqueous solution; pH 3.0–10; 25–40 °C | PFOS = 1455.6 mg/g PFOS = 1601.2 mg/g | Electrostatic interactions | (Yu et al., 2008) |
| Chitosan-coated fluoro-functionalized COF | Chitosan | Chitosan coating via ionic cross-linking with sodium tripolyphosphate | DI water, lake water, and sewage; pH not specified; 25 °C | PFOS = 8307.1 mg/g PFOA = 6177.1 mg/g GenX = 4603.3 mg/g | Electrostatic interactions, Hydrogen bonding, Fluorine–fluorine interactions, Channel size-selection | (He et al., 2022) |
| PEI-functionalized cellulose microcrystals | Cellulose microcrystals | PEI-functionalized cellulose via TEMPO oxidation and ion-exchange | Distilled water; pH 6.5; ambient temperature | PFOA = 2.32 mg/g | Electrostatic interactions | (Ateia et al., 2018) |
| Quaternary-ammonium-grafted flax fibers | *Phormium tenax* (New Zealand flax, cellulose-based fibers) | Two-step ATRP grafting of poly(2-methacryloyloxyethyl trimethylammonium chloride) (PMETAC) | Milli-Q water; pH 6.02; 22 °C | PFBS = 43 mg/g PFBA = 5.7 mg/g PFPrA = 6.2 mg/g | Electrostatic and hydrophobic interactions | (Data et al., 2025) |
| Amine-functionalized β-cyclodextrin polymer | β-cyclodextrin (derived from starch) | Crosslinked with nitrogen-containing tripodal linkers (e.g., tris(2-aminoethyl)amine) | Purified water; pH 7; ambient temperature | PFOA = 457 mg/g GenX = 222 mg/g | Host-guest inclusion, Electrostatic interaction | (Yang et al., 2020) |
| Benzyl chloride β-cyclodextrin | β-cyclodextrin (derived from starch) | β-cyclodextrin modified with benzyl chloride | Nano-pure water; neutral pH; ambient temperature | – | Hydrophobic interactions | (Abaie et al., 2024) |
| β-cyclodextrin-decafluorobiphenyl (DFB) polymer | β-cyclodextrin (derived from starch) | Crosslinked with (DFB) via nucleophilic aromatic substitution | Aqueous solution; pH 3.0; 24 ± 1 °C | PFOS = 43.10 ± 4.30 mg/g | Host-guest inclusion (Hydrophobic interaction), Electrostatic interaction | (Verma et al., 2025) |
| Amino- and fluorine-functionalized high-swelling cyclodextrin polymer | β-cyclodextrin (derived from starch) | Dual functionalization with trifluoroethylamine (TFEA) and poly(dimethylaminoethyl methacrylate) (pDMAEMA) | Aqueous solution; pH 6.57; 25 °C | PFOA = 826.8 mg/g PFBS = 316.5 mg/g PFPeA = 228.6 mg/g PFDA = 936.8 mg/g GenX = 251.7 mg/g PFHxA = 616.3 mg/g | Electrostatic attraction, Hydrophobic interaction, Fluorine-fluorine interaction, Host-guest inclusion | (Zhang et al., 2025) |

hydrophobic interactions with fluorinated tails. RAPIMER achieved exceptional adsorption capacities of 3529 mg/g for PFOA and 4151 mg/g for PFOS, with >98% removal under continuous-flow conditions. Its structural stability, biodegradability, and dual adsorption–biodegradation functionality make it a promising next-generation biosorbent (Li et al., 2022).

Taken together, the studies discussed in Sections 2.1–2.4 highlight differences in adsorption behavior among the reviewed adsorbents. As reflected in Tables 1 and 2, adsorption is influenced by PFAS chain length, with stronger interactions typically observed for long-chain compounds and weaker affinity for short-chain PFAS, particularly with carbon-based materials. Additionally, surface chemistry and modification strategies are crucial, as functional groups and material structure influence adsorption performance for both carbon-based and other biomass-derived sorbents, including chitosan- and cyclodextrin-based materials. However, the reported adsorption capacities and removal efficiencies vary widely depending on the material type and experimental conditions, indicating that performance is highly system-dependent.

## 3. Adsorption mechanisms

PFAS are persistent compounds exhibiting both hydrophobic and hydrophilic traits. While some PFAS with higher $pK_a$ values, such as

perfluorooctanesulfonamide (PFOSA), may exist partially in a neutral form at low pH, most PFAS have low $pK_a$ values and mainly exist as anions in water (Du et al., 2014). Their negative charge results from the strong electron-withdrawing effect of fluorine atoms, which increases the acidity of terminal carboxylate ($–COO^-$) and sulfonate ($–SO_3^-$) groups. Hydrophobicity mainly depends on the length of the perfluorinated chain (Vakili et al., 2024). These structural aspects influence how PFAS interact with adsorbent surfaces and form the basis for the adsorption mechanisms described below.

### 3.1. Electrostatic interaction

Electrostatic interactions play a significant role in PFAS adsorption, as PFAS exist primarily as anionic species in solution due to their low $pK_a$ values (Fig. 2**a**) (O'Connor et al., 2022). Positively charged adsorbent surfaces can therefore strongly attract PFAS anions. This mechanism is especially critical for removing short-chain PFAS (e.g., PFBA, PFBS), which rely more on electrostatic forces than on hydrophobic interactions due to their shorter perfluorinated tails and higher solubility (S. Deng et al., 2012; Fagbayigbo, Opeolu, Fatoki, Akenga, & Olatunji, 2017; Hernandez et al., 2022; Li et al., 2022; Zhang et al., 2023; Hassan et al., 2020). Furthermore, as PFAS accumulate on the surface, the net positive charge diminishes and steric hindrance increases, both of which can limit further adsorption. For instance, Zhang et al. found that electrostatic attraction was the dominant mechanism for PFOS and PFOA removal by an acid-modified sludge-derived biochar (H-SL) (Zhang et al., 2023). The highest adsorption capacity occurred at pH 3, when the surface was positively charged, and decreased significantly as pH rose and the zeta potential became negative. Molecular simulations by Choudhary et al. further clarified this mechanism for a β-CDP crosslinked with fluorinated aromatic linkers (Choudhary, Dong, Tsianou, Alexandridis, & Bedrov, 2022). Positively charged ammonium counterions bind tightly to the hydroxyl groups of β-CD, forming localized positive sites that electrostatically attract the anionic PFOA headgroups. Networks that inhibit these ammonium-CD interactions show significantly reduced PFOA adsorption, highlighting the importance of mediated electrostatic attraction. Additionally, in systems where both PFAS and adsorbent surfaces carry a negative charge, monovalent and divalent cations (e.g., $K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Mn^{2+}$) can often create a bridging effect by linking the negatively charged PFAS headgroups to the negatively charged adsorbent surfaces (Sleep, Miklavcic, & Juhasz, 2023).

### 3.2. Hydrophobic interaction

Hydrophobic interactions are crucial for PFAS adsorption, particularly onto carbon-based materials. This mechanism occurs via direct interaction between the hydrophobic PFAS tails and the hydrophobic surfaces of the adsorbents, or through self-aggregation, which leads to the formation of structures like bilayers, micelles, or hemimicelles (Fig. 2**b**) (Kabiri, Monaghan, Navarro, & McLaughlin, 2024; Yin & Villagrán, 2022). Hydrophobic interactions, driven entropically, promote aggregation of hydrophobic moieties in aqueous systems and are the dominant adsorption mechanism for long-chain PFAS such as PFOS, PFOA, perfluorononanesulfonic acid (PFNS), and perfluorodecanoic acid (PFDA) (Meservey et al., 2024; Wang et al., 2025). Despite electrostatic repulsion, many studies have shown that anionic PFAS, particularly long-chain species, can effectively adsorb onto negatively charged surfaces when hydrophobic interactions dominate (Chen, Xia, Wang, Qiao, & Chen, 2011; Deng et al., 2015). This is evidenced by high PFAS removal at elevated pH, where electrostatic attraction diminishes but hydrophobic forces remain strong (Gagliano et al., 2020). While PFAS can form micelles above their critical micelle concentration, such conditions are rare environmentally. Instead, adsorption typically proceeds via initial binding of individual PFAS molecules, followed by aggregation as sorbent pores become increasingly saturated. For example, alginate-encapsulated rice straw biochar achieved up to 99.9% PFOS removal (versus ~ 39% for PFBS), with hydrophobic interactions identified as the primary mechanism. The minimal influence of pH and ionic strength on removal efficiency further confirmed the dominance of hydrophobic affinity over electrostatic interactions (Militao et al., 2023).

### 3.3. Hydrogen bonding

Hydrogen bonding can also contribute to PFAS adsorption, where oxygen atoms in PFAS headgroups act as acceptors for hydrogen donors (e.g., –NH, –OH, and –COOH) on the adsorbent surface (Fig. 2**c**). For example, in a study by Weiss-Errico and O'Shea, the interaction behavior of β-CD and its positively charged derivatives was evaluated

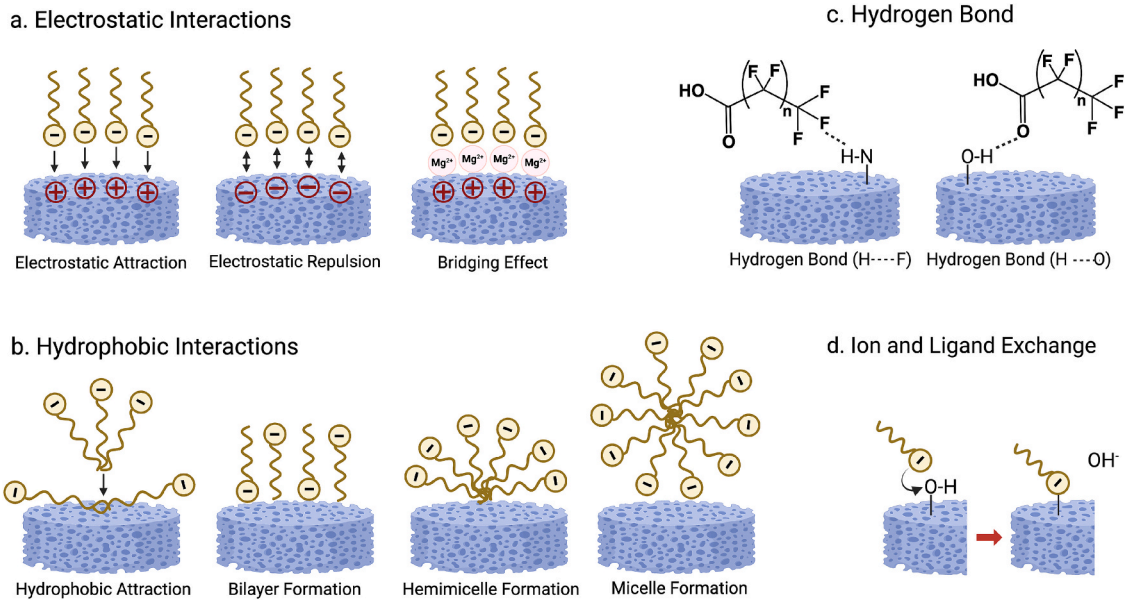


**Fig. 2.** Adsorption mechanism between adsorbents and PFAS in aqueous solutions: (**a**) Electrostatic interactions, (**b**) Hydrophobic interactions, (**c**) Hydrogen bonding, (**d**) Ion and ligand exchange.

with a range of short-chain PFAS (including PFBA, perfluorophosphonic acid (PFPA), perfluoro-4-methoxybutanoic acid (PFMOBA), GenX, perfluoro-3-methoxypropanoic acid (PFMOPrA), and perfluoro(5-oxa-6-dimethylhexanoic) acid (PFDMMOBA)) (Weiss-Errico & O'Shea, 2019). They highlighted that while the primary driving force for PFAS removal was hydrophobic (centered on van der Waals interactions between the fluorinated chains and the β-CD's hydrophobic cavity), hydrogen bonding also played an important stabilizing role. In particular, when PFAS species orientated their carboxylate headgroups toward the narrow opening of β-CD, the primary hydroxyl groups of β-CD formed hydrogen bonds with the PFAS headgroups and further stabilized the complex. The study showed that for certain PFAS like PFDMMOBA, this hydrogen bonding significantly enhanced the host–guest complex. Interestingly, when β-CD derivatives with added positive charges were used, the dual stabilization of hydrogen bonding and electrostatic attraction further increased PFAS binding affinity. The authors underscored that while hydrophobic interactions dominate encapsulation, hydrogen bonding between PFAS headgroups and the CD rim provided additional significant binding strength (in complexes without the extensive fluorocarbon segments).

The importance of hydrogen bonding remains debated. Although C–F chains are not hydrogen bond donors due to their hydrophobicity, the headgroup oxygen atoms in PFAS have been shown to act as effective hydrogen bond acceptors (He, Pan, & Zhang, 2013; Takayose, Nishimoto, & Matsui, 2012). The net contribution depends on the adsorbent: in some systems it plays a key role, while in others it may be minimal or even counterproductive. For example, increasing the density of carboxyl and hydroxyl groups on carbon nanotubes (CNTs) has been shown to reduce PFAS adsorption compared to pristine CNTs, likely because these hydrophilic, oxygen-containing groups preferentially bind water molecules, compete with PFAS for surface access, and block hydrophobic adsorption sites (Li et al., 2011).

### 3.4. Ion and ligand exchange

PFAS adsorption can also occur via exchange reactions, where anionic PFAS headgroups displace surface-bound hydroxyls or counterions on adsorbents such as metal oxides and ion-exchange resins (Dixit, Barbeau, Mostafavi, & Mohseni, 2019). These processes are distinct: anion exchange occurs when PFAS anions exchange with pre-adsorbed counterions (i.e., $Cl^-$ or $CO_3^{2-}$) on resin surfaces, whereas ligand exchange occurs when PFAS headgroups (e.g., carboxylates or sulfonates) displace surface hydroxyls on metal oxides (Fig. 2**d**). For anion-exchange resins, the primary mechanism is stoichiometric displacement of counterions. Deng et al. demonstrated this for PFOS removal, observing a near 1:1 molar ratio between PFOS sorption and $Cl^-$ release at low concentrations. At higher concentrations, sorption exceeded $Cl^-$ release, indicating contributions from additional mechanisms such as multilayer adsorption and hydrophobic interactions within resin pores (Deng, Yu, Huang, & Yu, 2010). Similarly, Ahrens et al. confirmed the anion-exchange mechanism by correlating PFAS adsorption with $Cl^-$ release from strong-base resins (Ahrens, Lundgren, McCleaf, & Köhler, 2025). In contrast, PFAS can bind to metal oxides (e.g., aluminum oxide or iron oxide) via ligand exchange, where surface hydroxyl groups are displaced to form covalent metal–ligand complexes (Gao & Chorover, 2012; Wang, Liu, & Shih, 2012). Gao and Chorover provided direct spectroscopic evidence (FTIR shifts) that PFOA adsorbs onto iron oxide nanoparticles ($\alpha$-$Fe_2O_3$) through inner-sphere Fe–carboxylate complexation at low pH, where surface Fe–$OH_2^+$ groups are abundant. In contrast, PFOS on the same surface exhibited no ligand exchange, adsorbed primarily through outer-sphere electrostatic interactions and hydrogen bonding (Gao & Chorover, 2012).

### 3.5. Synergistic and competing adsorption mechanisms

In practical systems, PFAS adsorption rarely proceeds through a single dominant interaction; instead, multiple mechanisms operate simultaneously, with their relative contributions governed by solution chemistry and PFAS molecular structure. Electrostatic attraction and hydrophobic interactions frequently compete: electrostatics primarily control short-chain PFAS adsorption under acidic conditions or on positively charged surfaces, whereas hydrophobic interactions dominate long-chain PFAS uptake, particularly at neutral to alkaline pH where electrostatic forces are weakened (Smaili & Ng, 2023). Increasing ionic strength further suppresses electrostatic interactions through charge screening and competition from background anions, shifting adsorption toward hydrophobic partitioning or secondary mechanisms (McCleaf et al., 2017). Cation bridging represents a key synergistic pathway that couples electrostatic and hydrophobic mechanisms. In systems where both PFAS and adsorbent surfaces are negatively charged, divalent cations such as $Ca^{2+}$ and $Mg^{2+}$ can coordinate with PFAS headgroups and surface functional groups, reducing electrostatic repulsion and anchoring PFAS at the interface (Nguyen et al., 2025). This mediated attachment facilitates subsequent hydrophobic interactions between fluorinated tails and nonpolar surface domains, particularly under environmentally relevant ionic conditions. Synergistic effects are most pronounced in adsorbents containing both ionic and hydrophobic domains, where PFAS headgroups interact electrostatically while fluorinated tails partition into nonpolar regions, yielding higher overall affinity than either mechanism alone (Weiss-Errico & O'Shea, 2017). In contrast, hydrogen bonding generally plays a secondary or stabilizing role and, due to its weaker strength relative to water hydrogen bonding, contributes less significantly under aqueous conditions. This effect has been attributed to the tendency of surface polar functional groups to preferentially interact with water molecules, which can hinder PFAS access to hydrogen-bonding sites and reduce overall adsorption efficiency, especially on oxygen-rich surfaces (Hamza, Ayinla, Elsayed, & Hassan, 2025; Li et al., 2011). Overall, PFAS adsorption reflects a balance of competing and cooperative interactions that varies with pH, ionic composition, and PFAS chain length. Recognizing this interplay is essential for interpreting adsorption behavior and guiding the design of biomass-based adsorbents for complex water matrices.

## 4. Adsorbent modification strategies for improved PFAS removal

The removal efficiency of biomass-based adsorbents for PFAS can be greatly improved through targeted surface and structural modifications. These strategies aim to overcome issues such as low affinity for short-chain PFAS, limited surface functionality, and slow adsorption rates by enhancing surface charge, boosting hydrophobic interactions, and creating nanoscale porosity. This section reviews major modification techniques, including enhancing surface charge, hydrophobicity enhancement, and nanoscale engineering, that are designed to maximize PFAS adsorption while preserving the sustainability of biomass-based materials.

### 4.1. Surface charge enhancement

To effectively enhance the removal of PFAS, it is vital to modify the surface charge of adsorbents to boost their electrostatic attraction to anionic PFAS. This modification is essential for targeting short-chain PFAS, which rely heavily on electrostatic interactions due to their limited hydrophobic character. Positively charged biomass-based adsorbents can be produced by incorporating amine-containing functional groups or adding cationic species to the surface (Ateia et al., 2018). Chitin and chitosan, which are naturally derived polysaccharides, show great promise due to their inherent amine groups that can be activated or enhanced via deacetylation. However, it should be noted that excessive deacetylation can lead to chitosan becoming water soluble, which may compromise its structural integrity during treatment. To address this challenge, quaternary ammonium groups can be grafted onto the chitosan backbone, resulting in materials with improved pH

stability and increased electrostatic affinity for anionic PFAS. These groups remain positively charged over a wide pH range (3–10), enhancing PFAS removal in varying environmental conditions. For example, quaternized chitosan materials have shown better performance and pH stability in PFAS treatment. Similarly, quaternized cotton and aminated rice husk were synthesized through atom transfer radical polymerization. These materials demonstrated significant PFAS adsorption due to the abundance of amine groups on their surfaces, facilitating the electrostatic attraction between the protonated amine groups and the anionic PFAS (Deng et al., 2013; Deng et al., 2012). Deng et al. developed a quaternized cotton adsorbent by grafting quaternary ammonium groups onto cotton fibers, successfully capturing anionic PFAS (Deng et al., 2012). This material exhibited rapid and efficient removal, achieving equilibrium within a few hours, showcasing high sorption capacities of 1348.6 mg/g for PFOA and 1779.4 mg/g for PFOS. Furthermore, the adsorbent showed consistent sorption efficiency over a broad pH range (3–10), with minimal effect from pH-dependent protonation of remaining tertiary amine groups. These capacity values are among the highest recorded for biomass-based adsorbents, attributed to the strong electrostatic attraction from quaternary sites, and effectiveness maintained over broad pH variations. In a similar study, Huang et al. synthesized a quaternized cellulose-functionalized resin by attaching quaternary ammonium groups to cellulose, which was then anchored onto a polystyrene matrix (Huang, Fu, Fang, & Luo, 2025). This configuration introduced a permanent positive charge to the adsorbent, facilitating robust electrostatic interactions with anionic PFAS. The material achieved over 99% removal efficiency for PFOA, PFOS, PFBS, and GenX at environmentally relevant concentrations (~1000 ng/L), with adsorption capacities of 68 mg/g for PFBS, 46 mg/g for PFOS, 35 mg/g for PFOA, and 31 mg/g for GenX. Spectroscopic analysis confirmed that quaternary ammonium groups (C—$N^+$) acted as the active binding sites. The resin exhibited consistent performance across a wide pH range (4–10), strong resistance to ionic competition, and excellent regeneration over multiple cycles. These results further highlight the efficacy of permanent surface charge functionalization in improving PFAS removal.

### 4.2. Hydrophobicity enhancement

Hydrophobic interactions are crucial in driving PFAS adsorption, as the fluorinated alkyl tails of PFAS prefer nonpolar surfaces over water (Meservey et al., 2024). Consequently, numerous studies have investigated ways to enhance the hydrophobic properties of adsorbents, especially those made from biomass, or to modify solution conditions to enhance PFAS affinity for sorbents (Collivignarelli et al., 2023; Dalahmeh, Alziq, & Ahrens, 2019; Inyang & Dickenson, 2017). By reinforcing van der Waals dispersion forces and the "fluorophobic" effect, these methods have led to significant improvements in PFAS removal efficiencies (He, Cheng, Gunjal, & Zhang, 2024). A key approach involves enhancing the carbon-rich, nonpolar nature of biomass-derived adsorbents. For instance, generating biochar at elevated pyrolysis temperatures results in a more graphitized, hydrophobic carbon structure with increased porosity. Meservey et al. demonstrated that sewage sludge biochar produced at 1000 °C (with a surface area of approximately 148 $m^2/g$) exhibited significantly improved PFAS adsorption compared to biochar created at lower temperatures; specifically, PFOS adsorption rose along with pyrolysis temperature and surface area (Meservey et al., 2024). The biochar produced at 1000 °C favored the sorption of long-chain PFAS over shorter chains, highlighting the importance of hydrophobic tail interactions. Overall, biochar and AC produced from lignocellulosic feedstocks exhibit stronger PFAS affinity when they possess greater hydrophobicity, characterized by higher aromatic carbon contents and reduced polar functional groups (Liang et al., 2024; Nasrollahpour, Pulicharla, & Brar, 2025). Another approach to enhancing hydrophobicity involves the surface functionalization of biomass-based adsorbents with nonpolar or amphiphilic groups (Magalhães et al., 2024). This can be achieved by grafting long-chain organic moieties, which introduce hydrophobic domains that promote the partitioning of PFAS from water (Hedayati, Nicomel, Abida, & Li, 2024). For instance, in one study, cellulose-based adsorbents were engineered with hydrophobic alkylamines to enhance PFAS binding. Cellulose fibers from wood were oxidized into dialdehyde cellulose nanofibers and subsequently functionalized with alkylamines of varying chain lengths (C4, C6, and C8) (Li et al., 2025). The longer C8-alkylamine chains resulted in notably greater PFAS (PFOA and PFOS) removal compared to the shorter C4 chains, attributed to the enhanced van der Waals interactions from the C8 tail. Although the cationic amine groups on these chains contribute to electrostatic attraction, the study found that increasing alkyl chain length significantly improved adsorption efficiency, indicating that hydrophobic interactions primarily drive PFAS uptake in these modified biosorbents.

### 4.3. Nanoscale engineering

In addition to surface chemistry, the physical structure and morphology of bio-based adsorbents play a crucial role in the efficient removal of PFAS. Nanoscale engineered biomass materials—such as nanocellulose, chitin nanofibers, and starch nanoparticles—offer considerable benefits, including enhanced surface area, abundant functional groups, and customizable surface modifications (Abouzeid, Khiari, El-Wakil, & Dufresne, 2019; Kumar & Narayan, 2025; Luo, Fu, Wang, & Luo, 2025; Voisin, Bergström, Liu, & Mathew, 2017). These nanoscale frameworks can also serve as foundations for further functionalization with metal ions, cationic groups, or nanoparticles, boosting PFAS adsorption efficiency. For example, cellulose-based nanomaterials, which generally carry negative surface charges (e.g., carboxyl or sulfonate groups), can be modified to increase surface positivity (Song, Zhu, Zhu, & Li, 2019). This can be achieved by covalently attaching cationic polymers or coordinating multivalent metal ions or metal oxide nanoparticles onto the surface (Li et al., 2025). These ions can bond with hydroxyl, carboxyl, or sulfonate groups to form hybrid materials exhibiting increased charge density and stability. Notably, adding magnetite nanoparticles to adsorbent matrices effectively enhances PFAS adsorption through both electrostatic attraction and inner-sphere complexation. One study found that chitosan-based adsorbents were engineered at the nanoscale to take advantage of chitosan's cationic properties, thereby enhancing available binding sites (Torkamani, Tarokh, & Baghdadi, 2025). For example, the addition of carbon black nanoparticles to chitosan hydrogel beads created a highly porous network with a hollow nanoscale structure, resulting in an impressive PFOS adsorption capacity of approximately 359 mg/g (at pH 2), which is significantly better than that of unmodified chitosan beads. Starch-derived nanomaterials have also demonstrated advantages. Similarly, starch-stabilized magnetite nanoparticles resist aggregation and provide enhanced surface accessibility, resulting in a 2.4-fold increase in PFOA uptake ($q_{max} \approx 62.5$ mg/g) compared to non-stabilized particles (Gong, Wang, Liu, Tang, & Zhao, 2016). These examples highlight that designing biomass adsorbents with nanoscale characteristics (such as ultrafine fibers, nanoscale pores, or colloidal structures) can significantly enhance PFAS adsorption capacity and kinetics. This improvement arises from increased surface area and diverse interactions (including hydrophobic, electrostatic, and host–guest inclusion) that contribute to more effective remediation. Table 3 outlines the major modification strategies for biomass-based adsorbents, emphasizing their key mechanisms, the PFAS classes they target, their performance advantages, and associated trade-offs discussed in this section.

## 5. Regeneration and post-use challenges of PFAS-laden biomass-based adsorbents

Regenerating biomass-based PFAS adsorbents is essential for minimizing material consumption, operational expenses, and secondary

**Table 3**
Modification strategies for improving PFAS adsorption by biomass-based adsorbents.

| Modification Strategy | Primary Objective | Key Mechanisms | Target PFAS | Key Advantages | Main Limitations / Tradeoffs | Reference |
|---|---|---|---|---|---|---|
| Surface charge enhancement | Increasing affinity for anionic PFAS | Electrostatic attraction (anionic PFAS affinity) | Short-chain (e.g., PFBA, PFBS, GenX) | High affinity at low concentration; wide pH range | Solubility; Ionic competition; synthesis complexity | (Ateia et al., 2018; Deng et al., 2013; Deng et al., 2012) |
| Hydrophobicity enhancement | Strengthening interactions with fluorinated alkyl tails | Hydrophobic/ fluorophobic interactions (tail-group binding) | Long-chain (PFOA, PFOS) | High capacity for long-chain PFAS | Less effective for short-chain; high-temperature processing | (He et al., 2024; Hedayati et al., 2024; Li et al., 2025; Liang et al., 2024; Meservey et al., 2024; Nasrollahpour et al., 2025) |
| Nanoscale engineering | Increasing accessible surface area and adsorption kinetics | Nanoscale porosity, high surface-to-volume ratio, multifunctional binding sites | Broad range (chain-dependent) | Rapid uptake; high capacity; tunable surface chemistry | Aggregation; scale-up challenges | (Abouzeid et al., 2019; Luo et al., 2025; Torkamani et al., 2025) |
| Metal/ nanoparticle incorporation | Introducing additional binding sites and multifunctionality | Electrostatic/ complexation; magnetic separation | Short- to mid-chain PFAS | Improved selectivity; easy separation | Potential metal leaching; added synthesis steps | (Gong et al., 2016) |
| Combined/hybrid modification | Addressing multiple PFAS limitations simultaneously | Synergistic electrostatic, hydrophobic, and structural effects | Mixed PFAS systems | Broad-spectrum performance; tailored design | High complexity & cost | (Ateia et al., 2018; Li et al., 2025; Torkamani et al., 2025) |

waste. However, regeneration effectiveness varies significantly depending on adsorbent composition and the method used, often involving trade-offs between desorption efficiency, energy input, and cost per cycle. Common regeneration techniques include thermal treatment, solvent washing, chemical elution, as well as newer hybrid or destructive methods (Andrunik & Smol, 2025). Table 4 provides an overview of reported regeneration efficiencies, energy needs, and primary cost factors for various biomass-derived PFAS adsorbents. Thermal regeneration is most widely applied to carbonaceous adsorbents like biochar and activated carbon because of their high thermal stability. Heating media loaded with PFAS to moderate temperatures (~500–800 °C) can regenerate much of their adsorption capacity, achieving desorption efficiencies of approximately 75–99% per cycle, especially for long-chain PFAS (Andrunik & Smol, 2025; Vakili et al., 2024). However, repeated high-temperature treatment can cause adsorbent mass loss and structural degradation, and industrial reactivation of carbon typically results in ~15–30% media burn-off per cycle and gradual pore collapse at elevated temperatures (Ling et al., 2025). Thermal regeneration is energy-intensive, with reported energy demands of ~1.8–3.3 kWh/kg of regenerated carbon and associated costs of approximately $2.0–2.9 per kg for off-site reactivation (Ling et al., 2025). Complete PFAS destruction typically requires temperatures exceeding ~1,000 °C, which calls for specialized equipment and precise control to avoid releasing fluorinated byproducts (DiStefano, Feliciano, Mimna, Redding, & Matthis, 2022; Duchesne et al., 2020). Solvent-based regeneration effectively desorbs PFAS under mild conditions and typically preserves the adsorbent's structure over multiple cycles. Alcohol-based and mixed-solvent systems disrupt hydrophobic and ionic interactions, restoring over 90% of adsorption capacity in one cycle and maintaining more than 80% over multiple cycles for both carbon-based and polymer-based sorbents (Shaikh & Nawaz, 2025). Since regeneration takes place at ambient or slightly elevated temperatures, physical degradation and pore collapse are minimal compared to thermal methods. The energy required is relatively low, mostly for pumping and solvent recovery, but overall costs depend on solvent recycling and handling of PFAS-concentrated regenerant streams. Although solvent regeneration is generally cost-effective compared to replacing media, dealing with PFAS-laden solvent waste remains a significant operational challenge (Andrunik & Smol, 2025). Chemical regeneration using alkaline, saline, or pH-modified solutions provides a low-energy option and has been explored for biomass-based adsorbents (Deng et al., 2023). Reagents such as NaOH, salts, or ammonia can disrupt electrostatic interactions and improve PFAS desorption, with reported efficiencies generally ranging from ~70–95%, depending on adsorbent properties and operating conditions. These processes operate at ambient or moderately elevated temperatures, resulting in lower energy consumption than thermal methods. Nonetheless, the success of regeneration heavily depends on reagent strength: aggressive chemical conditions may damage surface functionalities or polymer structures. Proper handling of PFAS-contaminated regenerant solutions is essential to

**Table 4**
Comparison of regeneration methods for PFAS-laden biomass-based adsorbents in terms of typical performance metrics.

| Regeneration Method | PFAS Desorption Efficiency (%) | Adsorbent Loss/ Degradation | Energy Required | Cost per Regeneration Cycle | Reference |
|---|---|---|---|---|---|
| Thermal regeneration | 75–99% capacity restored (often ≥ 90% for long-chain PFAS) | Moderate burn-off (15–30% mass loss per cycle) due to carbon oxidation; possible pore collapse at > 800 °C | High: ~500–900 °C needed for desorption; ~1.8–3.3 kWh/kg energy use | High: ~$2–3 per kg adsorbent (off-site reactivation) | (Andrunik & Smol, 2025; DiStefano et al., 2022; Duchesne et al., 2020; Ling et al., 2025; Vakili et al., 2024; Vilén, Laurell, & Vahala, 2022) |
| Solvent-based regeneration | >90% recovered in first cycle; ~80–95% retained over multiple cycles | Minimal: physical degradation; pore structure intact over repeats | Low: ambient–mild heating; ~2–3 kWh/kg including solvent recovery | Moderate: ~$2.6–4.0 per kg adsorbent; additional cost for PFAS waste destruction | (Andrunik & Smol, 2025; Chaudhary, Usman, Mašek, Haderlein, & Hanna, 2025; Ling et al., 2025; Yousif et al., 2025) |
| Chemical regeneration | 70–95% desorption in initial cycles; performance depends on regenerant composition | Possible degradation under strong alkaline or oxidative conditions; depends on adsorbent and regeneration | Low: ambient or mild heating; energy mainly for mixing and pumping | Low–moderate; depends on chemical consumption and treatment of PFAS-laden regenerant | (Deng et al., 2023) |
| Emerging (e.g., electrochemical/ hydrothermal) | >90% PFAS removal or partial mineralization (lab-scale) | Limited scalability; system complexity; uncertain long-term adsorbent stability | Variable; often high for hydrothermal methods | Not yet well defined (lab/ pilot stage) | (Ersan et al., 2023) |

avoid secondary contamination and to manage overall treatment costs (Restrepo-Osorio & O'Shea, 2025). Emerging regeneration methods, such as electrochemical, hydrothermal, and advanced oxidation or reduction processes, focus on regenerating adsorbents and breaking down PFAS, thereby reducing secondary waste. Lab results are promising, demonstrating effective PFAS removal and partial mineralization, but these techniques remain limited by system complexity, high energy consumption, or uncertain scalability (Ersan, Ersan, Perreault, & Garcia-Segura, 2023; Restrepo-Osorio & O'Shea, 2025). Overall, no single regeneration strategy is universally optimal. Methods that achieve high PFAS desorption rates usually need more energy or generate secondary waste. In contrast, energy-efficient methods might not fully desorb PFAS or could harm the adsorbent's long-term durability. The lack of standardized data on regeneration efficiency, energy use, cost per cycle, and multi-cycle performance limits current research, making it difficult to compare methods and choose the best approach for biomass-based PFAS adsorbents.

## 6. Research needs and future directions

### 6.1. PFAS sorbent design under selectivity and fouling constraints

A key challenge in PFAS remediation is achieving sufficient selectivity at environmentally relevant concentrations. While many biomass-based adsorbents demonstrate high PFAS adsorption in laboratory studies, in real-world conditions PFAS are usually present at trace levels compared to non-fluorinated organic matter and inorganic ions, which makes competitive adsorption unavoidable (He et al., 2024; Tshangana et al., 2025). Limited selectivity allows competing species to occupy adsorption sites, reducing PFAS uptake capacity. Notably, natural organic matter (NOM) tends to strongly adsorb onto carbon-based materials, blocking pores and masking active sites (McNamara, Franco, Mimna, & Zappa, 2018). Adsorption challenges are increased due to the molecular diversity of PFAS. Short-chain PFAS, such as PFBS and PFBA, have lower hydrophobicity and higher solubility in water compared to long-chain compounds, resulting in weaker interactions with many biomass-derived sorbents (Liang et al., 2024). As a result, materials designed specifically for PFOS or PFOA removal might not be effective against short-chain PFAS. Overcoming this challenge involves creating broad-spectrum sorbents with customized porosity and surface chemistry. Current approaches include adding electropositive or fluorophilic functional groups, adjusting pore-size distributions, and developing composite materials that utilize various interaction mechanisms (Tan et al., 2022). Enhancing intrinsic selectivity and fouling resistance remains a key materials-level challenge for biomass-based PFAS adsorbents. Although improvements in sorbent design can enhance intrinsic selectivity and fouling resistance, these material-level properties alone do not fully determine performance in real treatment scenarios, where flow dynamics and the complex water matrix impose additional limitations.

### 6.2. Real water matrix effects and scale-up challenges

Most PFAS adsorption studies on biomass-based materials have been conducted at the bench scale with batch experiments and simplified water samples. However, applying these findings to real-world treatment systems presents additional challenges due to water matrix complexity and scale-up. Natural and wastewater-affected waters contain dissolved organic matter (NOM), background ions, and suspended solids that compete for adsorption sites, alter surface charges, and speed up breakthrough in flow-through systems. Column studies have shown that adsorption capacities estimated from batch tests often overstate actual removal performance when factors like hydrodynamics, mass transfer limitations, and exposure to complex water matrices are taken into account (Dalahmeh et al., 2019; Inyang & Dickenson, 2017; Mulugeta, Ersan, Garcia-Segura, & Ersan, 2025). In particular, dissolved organic matter and background ions have been found to reduce electrostatic interactions, block pore access, and decrease bed lifespan in column systems treating real waters, leading to earlier PFAS breakthrough than expected from bench-scale predictions (Dalahmeh et al., 2019; Mulugeta et al., 2025). Biochar filter columns and biochar-amended bioretention systems demonstrate this limitation by effectively removing long-chain PFAS but allowing short-chain species to breakthrough quickly under environmentally relevant flow and saturation (Hawkins et al., 2024). Likewise, biomass-derived cyclodextrin polymer granules and functionalized cellulose-based materials have shown promising PFAS adsorption in laboratory-scale packed-bed configurations, yet their performance is highly affected by competing solutes and hydraulic residence time, raising uncertainties for scale-up (Ching, Lin, Dichtel, & Helbling, 2023; Harris, de la Garza, Devlin, & McNeil, 2022). These results underscore the importance of real-world water matrix effects and system-level transport processes for PFAS removal effectiveness. Therefore, conducting systematic column-scale tests with realistic water chemistries is crucial to evaluate the practical potential and scalability of biomass-based adsorbents.

### 6.3. Sustainability and life-cycle considerations

Beyond adsorption performance and regeneration efficiency, the deployment of biomass-based PFAS adsorbents must be evaluated within a broader sustainability framework. Life-cycle aspects such as feedstock sourcing, material processing, operational lifetime, and waste disposal are crucial for understanding environmental impact. Consequently, techno-economic analysis (TEA) and life-cycle assessment (LCA) are increasingly advised to compare trade-offs between material costs, regeneration needs, and disposal options (Lei et al., 2023). In addition, regulatory acceptance and public concerns about PFAS handling underscore the need for transparent evaluation of long-term risks associated with spent adsorbents. Integrating performance metrics with sustainability and risk assessments will be essential to guide the responsible implementation of biomass-based PFAS remediation technologies (Tshangana et al., 2025).

## 7. Conclusions

This review explores biomass-based adsorbents' potential for removing PFAS from contaminated environments. It covers carbonaceous materials like biochar and activated carbon, cellulose-derived adsorbents, protein-based sorbents, and other natural polymers, highlighting their affordability, renewability, and customizable surface features. These traits make them suitable for PFAS cleanup across various settings. The review discusses modification techniques, such as amine functionalization, hydrophobic tailoring, nanoparticle addition, and nanoscale engineering, showing how these enhance PFAS adsorption. Mechanistic insights into hydrophobic interactions, electrostatic attraction, hydrogen bonding, and ligand exchange support their effectiveness against both short- and long-chain PFAS. Post-application challenges are also addressed, emphasizing that PFAS-contaminated sorbents become secondary waste requiring proper disposal through thermal destruction, regeneration, or secure landfilling, with each route presenting distinct environmental trade-offs. Overall, this review demonstrates that biomass-based adsorbents offer a scalable, eco-friendly solution for PFAS remediation, supported by growing evidence for their continued development and implementation in engineered systems and broader environmental management.

## CRediT authorship contribution statement

**Neda Arabzadeh Nosratabad:** Writing – review & editing, Writing – original draft. **Qiangu Yan:** Writing – review & editing, Conceptualization. **Zhiyong Cai:** Writing – review & editing, Conceptualization. **Caixia Wan:** Writing – review & editing, Supervision,

Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Declaration of generative AI use.**

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language polishing and improving clarity. The authors reviewed and edited the content and take full responsibility for the final manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

## Data availability

No data was used for the research described in the article.

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