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Advancements in antibiofouling hydrogel-based approaches for the removal of short-chain per- and polyfluoroalkyl substances in drinking water treatment

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Per- and polyfluoroalkyl substances (PFAS) are emerging contaminants with increasing health concern due to their persistence, widespread presence, and adverse health effects. Short-chain PFAS, in particular, are more challenging to remove using conventional water treatment technologies. Hydrogel adsorbents have shown as a promising solution for short-chain PFAS removal, offering high adsorption capacity, rapid kinetics, and tunable material properties. However, biofouling contamination which is easier to happen on wet hydrogels adsorbents compared with conventional adsorbents in water treatment process, could significantly reduce adsorption efficiency, shorten operational lifespan, and increase overall costs. Antibiofouling modifications present a viable strategy to enhance hydrogel functionality in drinking water treatment applications. This review summarizes recent advancements of hydrogel in antibiofouling and short-chain PFAS removal applications through functional group modifications. Furthermore, it highlights gaps in the current literature, particularly the lack of studies on the development and evaluation of hydrogels with both biofouling resistance and short-chain PFAS removal capabilities for drinking water treatment applications.

KEYWORDS

antibiofouling hydrogel, drinking water treatment, short-chain PFAS removal, long-term usage, domestic water treatment

1 Introduction

Promoting access to safe drinking water remains a critical global challenge, with the presence of emerging contaminants such as per- and polyfluoroalkyl substances (PFAS) posing significant risks to water quality and public health as a significant factor contributing to this issue (Stoiber et al., 2020; UNESCO, 2023). PFAS are persistent organic pollutants widely detected in drinking water due to industrial discharges, the use of firefighting foams and the disposal of consumer product waste into the environment (Stoiber et al., 2020; Munoz et al., 2023; Hu et al., 2016; Wang et al., 2020). Most PFAS are resistant to chemical degradation due to their strong C-F bonds (Bao et al., 2018; Verma et al., 2023; Ye et al., 2023). Short-chain PFAS (carbon chain ≤7), with a shorter fluorinated tail, were introduced

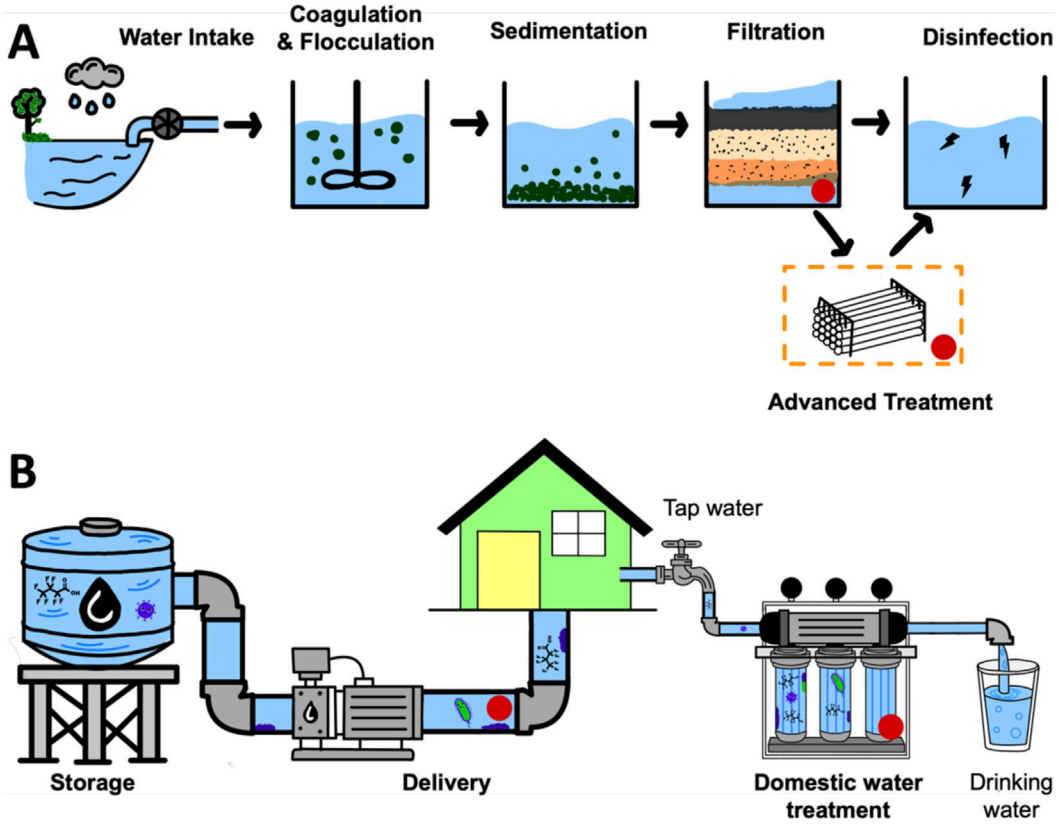

FIGURE 1
(A) Schematic graph of the drinking water treatment process includes water intake, coagulation, sedimentation, filtration, disinfection, and distribution. Advanced treatment technologies are used in some drinking water treatment systems to remove emerging contaminants like PFAS. Red spots indicate vulnerable stages exposed to potential biofouling risks. **(B)** Diagram of water distribution from storage to household use, highlighting potential biofouling risks in domestic water treatment systems and tap water supply, marked by red dots.

as safer alternatives to their long-chain counterparts (carbon chain ≥7) in industry applications in the past decades (Jensen and Warming, 2015). However, the smaller molecular size and increased hydrophilicity make short-chain PFAS difficult to remove (Brendel et al., 2018; Li et al., 2020), posing new challenges for water treatment. Moreover, short-chain PFAS have been widely detected in groundwater and treated drinking water with Liquid Chromatography-Mass Spectrometry and High-Resolution Mass Spectrometry through either direct injection or solid-phase extraction to concentrate the PFAS and clean the matrix background before injection (Ateia et al., 2019; Li et al., 2011; Wang et al., 2024a). And short-chain PFAS have been found to pose significant health risks, including lipid metabolism disruption, infertility, reproductive issues, and endocrine dysfunction (Sheng et al., 2018; Chen et al., 2018; Feng et al., 2017; Nian et al., 2020). Short-chain PFAS ammonium salt of hexafluoropropylene oxide dimer acid (GenX) has also been shown to induce liver toxicity in animal studies (Solan et al., 2023).

Advanced treatment process is an additional step incorporated in novel technologies to remove emerging contaminants like PFAS during water treatment processes, and has shown better PFAS removal effects from water than other treatment processes such as coagulation, flocculation, sedimentation, and filtration (Figure 1A; Seven seas water, 2023; Jafarinejad, 2025). Advanced treatment process is normally implemented before the disinfection process (Figure 1A). PFAS removal from drinking water primarily relies on activated carbon (GAC) (Kempisty et al., 2022) and ion exchange resins (IER) from advanced treatment process (Boyer et al., 2021). However, both adsorbents are more effective in removing long-chain PFAS than short-chain PFAS (Jafarinejad, 2025). Furthermore, short-chain PFAS adsorbed onto GAC can be displaced by longer-chain PFAS and other more hydrophobic compounds over time (Newcombe, 1994; Park et al., 2020), and the presence of other natural organic contaminants and ions in the water matrix could reduce the performance of these adsorbents due to competitive adsorption (Ateia et al., 2019).

In addition, biofouling is another challenge for most materials used for water treatment (LeChevallier et al., 1984; Wells and Sytsma, 2009; Nguyen et al., 2012; Abdelsalam et al., 2017). Although disinfection methods such as chlorination, ultraviolet irradiation, and advanced oxidation processes are widely employed to control bacterial growth, some bacteria can withstand these conventional treatments and remain in treated water (Sharma and Bhattacharya, 2017). Microorganisms present in flowing water can adhere to surfaces within drinking water treatment materials, distribution piping systems, as well as domestic treatment adsorbents or membranes (Bachmann and Edyvean, 2005; Sójka et al., 2023; Zuo et al., 2022; Daschner

et al., 1996), where they utilize accumulated nutrients to grow and form biofilms over time, ultimately leading to biofouling (Figure 1B). Biofilm formed on the surface of adsorbents can occupy the active sites on adsorbent materials (Flemming and Geesey, 1991) and clog membranes (Razali et al., 2023), thereby reducing the adsorption efficiency of adsorbents and compromising system performance by decreasing flux, permeability, and usage life over time. Despite this, effective antibiofouling strategies for these materials remain lacking for short-chain PFAS control applications. Hydrogel based adsorbents have emerged as a promising alternative to conventional adsorbents and filtration membrane for removing anion short-chain PFAS (Xu et al., 2024; Huang et al., 2018; Verduzco and Wong, 2020; Naim Shaikh and Nawaz, 2024). Comparing with GAC and IER, the hydrophilic, and porous nature of hydrogel and its tunable surface property makes it not only possible to be effective for short-chain PFAS removal but also with dual function of biofouling resistance after modification. These three-dimensional, cross-linked polymeric materials offer high water content, tunable porosity, and surface functionality, enabling them to interact effectively with water-soluble PFAS molecules through mechanisms like hydrophobicity, electrostatic interactions, hydrogen bonding, and size exclusion (Xu et al., 2024; Wang et al., 2025).

Although hydrogel-based adsorbents have been extensively studied for contaminant removal and antibiofouling separately, their potential to integrate both properties for efficient short-chain PFAS removal remains underexplored. However, this approach holds significant promise. For instance, hydrogel coatings on filtration membranes have been shown to impart antibiofouling properties in addition to contaminant removal (Sójka et al., 2023; Li et al., 2022).Additionally, graphene oxide-incorporated hydrogels have been reported to be effective for short-chain PFAS removal in one study (Becanova et al., 2021) and for antibiofouling in another (Zhang et al., 2018).

This review explores hydrogel adsorbents for short-chain PFAS removal and the challenges they face in engineering applications due to insufficient antibiofouling properties. Furthermore, it examines advancements in antibiofouling hydrogels for water treatment and the potential for enhanced performance by integrating antibiofouling features with effective PFAS removal components. It also highlights key insights and future directions for developing antibiofouling hydrogel technologies to improve short-chain PFAS removal in water treatment applications.

2 Hydrogels for short-chain PFAS removal

Hydrogel based adsorbents emerges as a highly effective alternative to traditional adsorbents for short-chain PFAS removal in water treatment, offering benefits as shown in Supplementary Table S1 such as faster kinetics, high affinity for short-chain PFAS, easy regeneration, and reusability (Ateia et al., 2019; Huang et al., 2018; Verduzco and Wong, 2020; Alsaka et al., 2025) comparing with GAC (Boyer et al., 2021; Zhang et al., 2021). Additionally, IER, the other conventional adsorbent, exhibits good adsorption capacity over multiple short-chain PFAS, however, it is costly and can experience performance declines in the presence of organic matter and competing ions in the water matrix (Wang et al., 2024a). Additionally, IER has a low regeneration rate of 27.5% and degrades over time, limiting its long-term applicability (Wang et al., 2024a; Liu et al., 2022).

2.1 Interaction mechanisms of reported functional groups on hydrogels for short-chain PFAS removal

2.1.1 Electrostatic interactions

Electrostatic interactions are the dominant mechanism for short-chain PFAS removal improvement (Xu et al., 2024; Huang et al., 2018; Kumarasamy et al., 2020). Positively charged aminated functional groups, such as quaternary ammonium ($[NR_4]^+$) (Huang et al., 2018; Kumarasamy et al., 2020), and amine($-NH_2$) (Xu et al., 2024) have been incorporated into hydrogels, imparting a positive charge to the adsorbent and facilitating strong electrostatic interactions with anionic short-chain PFAS (Supplementary Table S2). The hydrophilic property of hydrogels reduces this kind of adsorbents' diffusion resistance to short-chain PFAS, enhancing adsorption kinetics and affinity (Xu et al., 2024; Verduzco and Wong, 2020) and their porous structure exposes a higher density of charged polymers to PFAS compared to IER, leading to increased adsorption capacity (Ateia et al., 2019). Huang et al. (2018) developed aminated poly (ethylene glycol) diacrylate hydrogels with adsorption capacities 8 to 63 times higher than conventional adsorbents, particularly for short-chain PFAS such as perfluorobutanesulfonic acid (PFBS), perfluorobutanoic acid (PFBA), and GenX (Huang et al., 2018). Similarly, aminated polyacrylamide hydrogel foam in another study (Xu et al., 2024) demonstrated a rapid equilibration within 15 min and a high affinity for perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), and GenX, achieving removal rates exceeding 90%, while PFBA removal reached 82%. This was attributed to the synergistic effects of electrostatic interactions, hydrogen bonding, and hydrophobic interactions (Xu et al., 2024). All studies have also demonstrated that aminated hydrogels have stronger binding affinities for PFBS over PFBA (Ateia et al., 2019; Xu et al., 2024; Huang et al., 2018). The versatility of hydrogel material allows hydrogel to be fabricated into beads (McCarty, 2016), porous membrane (Cai et al., 2023), foams (Li et al., 2022), or coatings on various surfaces (Wibisono et al., 2015) depending on application requirements.

2.1.2 Hydrophobic interactions

In contrast to electrostatic interactions, hydrophobic interactions via fluorination have been explored as another strategy to enhance PFAS adsorption, by leveraging the like-like affinity between hydrogel's fluorinated surfaces and the perfluoroalkyl chains of PFAS, but this approach is less effective for short-chain PFAS (Huang et al., 2018; Verduzco and Wong, 2020; Koda et al., 2014). Koda et al. (2014) developed perfluoroalkane-functionalized star polymer microgels, which captured only 23% of short-chain PFAS like PFHxA, while the hydrogel adsorbent modified with amination alone achieved over 97% removal efficiency. Notably, the combination of fluorination with cationic functional groups on hydrogel adsorbents (Wang et al., 2025; Huang et al., 2018; Verduzco and Wong, 2020) showed no obvious enhancement in short-chain PFAS adsorption compared to adsorbents modified with cationic functional groups alone. Huang

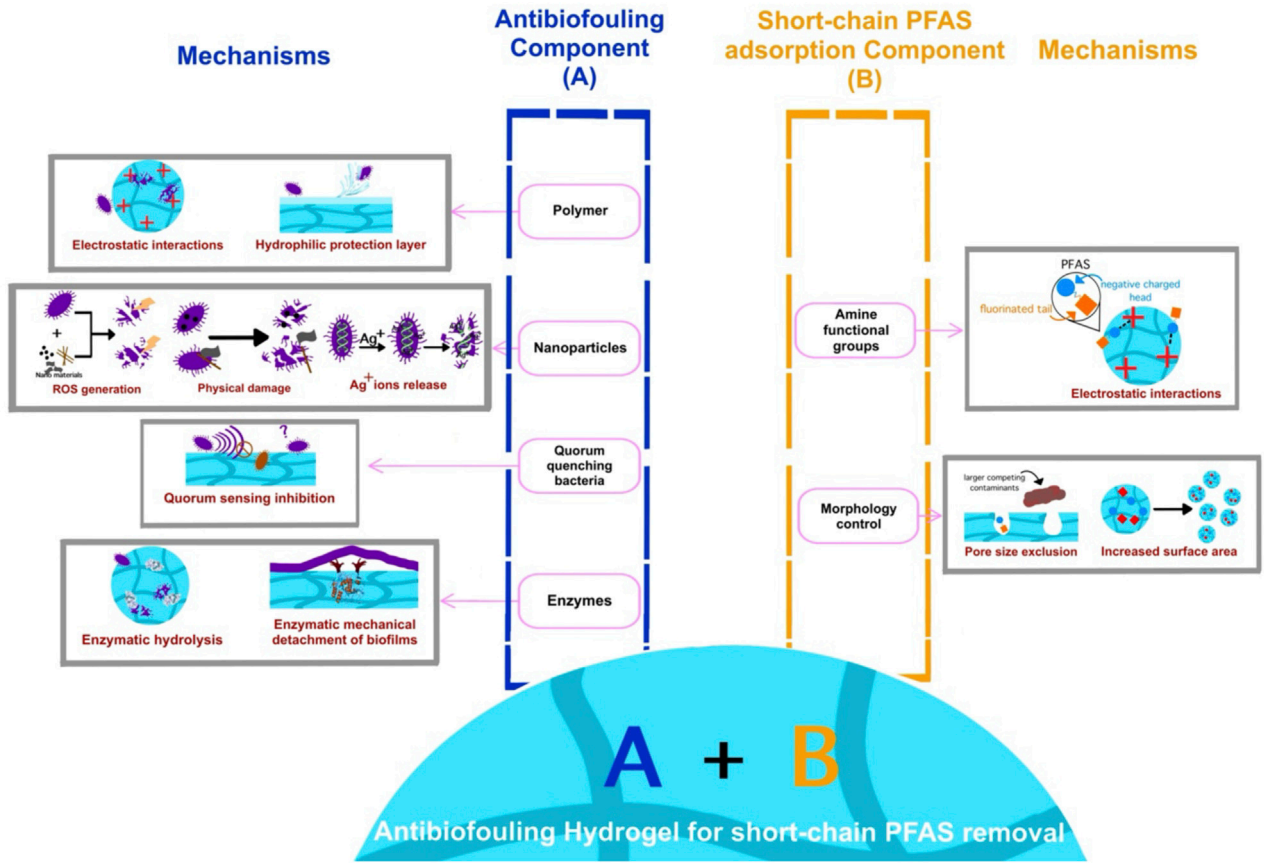

FIGURE 2
Schematic diagram of hydrogel modification strategies designed to impart both short-chain PFAS removal and antibiofouling properties, along with the underlying mechanisms of each strategy.

et al. (2018) observed that aminated hydrogels exhibited similar adsorption efficiencies to those containing both amination and fluorination, achieving 100% removal of PFBS and >95% removal of GenX, while non-fluorinated hydrogels performed better for PFBA removal. Given the limited effectiveness of fluorinated materials for short-chain PFAS removal and the potential release of PFAS from degraded fluorinated materials, fluorination strategy is not suggested for hydrogel based short-chain PFAS adsorbent development. Hence, electrostatic interactions remain the dominant mechanism for short-chain PFAS removal, particularly for compounds like PFBA and PFBS.

2.2 Selectivity and reusability of functionalized hydrogels

In addition, functionalized hydrogels with high reusability offers a higher practical advantage over GAC and IER (Supplementary Table S1), improving its practicality, scalability, and cost-effectiveness for future drinking water treatment applications. For example, Huang et al. (2018) demonstrated that their hydrogels could be easily regenerated in 70% methanol containing 1% NaCl and reused for up to 5 cycles before disposal, while mostly GAC were dumped to landfills for disposal or recycled for less than 3 times (Boyer et al., 2021). A report suggests potential for up to 10 cycles through optimizing material (Ateia et al., 2019), underscoring the hydrogels' potential for cost-effective, and sustainable use.

3 Antibiofouling hydrogels development for drinking water treatment

Nonetheless, biofouling contamination caused by colonization of attached bacteria on both conventional and emerging adsorbents is an inevitable challenge that decrease efficiency (LeChevallier et al., 1984; Abdelsalam et al., 2017; Flemming and Geesey, 1991; Wang et al., 2024b). Biofouling on hydrogel obstructs active adsorption sites and increases diffusion resistance for contaminants such as PFAS, degrades materials via enzymatic activity, ultimately shortening the operational lifespan of adsorbents and increasing maintenance costs (Flemming and Geesey, 1991; Vuong et al., 2023). Wang P. et al. (2022) found that PFAS passive sampling hydrogels exhibited significantly reduced adsorption performance after 21 days in surface water due to biofouling. Endowing hydrogel based materials with antibiofouling properties is crucial for ensuring their long-term efficacy while preventing secondary bacterial contamination to treated water.

Various antibiofouling strategies including polymers (Sójka et al., 2023; Li et al., 2022; Peng et al., 2022; Xu et al., 2023; Wen et al., 2021; Chen et al., 2024), nanoparticles (Zhang et al., 2018; Baek et al., 2015), quorum-quenching bacteria (Lee et al., 2018; Yi et al., 2024), and enzymes (Ye et al., 2019; Li et al., 2021; Zanoni et al., 2016) can be integrated into hydrogels designed to address this issue. These components inhibit biofilm formation through multiple mechanisms (Supplementary Table S3; Figure 2). The dominant antibiofouling mechanism is through electrostatic interactions, which causes bacterial membrane damage through the interaction between the oppositely charged polymer adsorbent and bacteria (Li et al., 2022; Chen et al., 2024; Wang J. et al., 2022). Hydrophilic protection is another mechanism that prevents biofouling contamination by forming a hydrophilic water layer on the adsorbent surface, thereby preventing bacterial attachment (Sójka et al., 2023; Zhang et al., 2018; Wibisono et al., 2015; Peng et al., 2022; Xu et al., 2023; Wen et al., 2021; Chen et al., 2024). Nanoparticles inhibit the formation of biofilm through physically breaking bacterial cells and chemically damaging bacteria membrane with generated reactive oxygen species (ROS) (Guo et al., 2021; Ye et al., 2017) or released toxic silver ions (Baek et al., 2015). In contrast, quorum-quenching bacteria and enzymes offer a more sustainable antibiofouling strategy (Lee et al., 2018; Yi et al., 2024; Ye et al., 2019; Li et al., 2021; Zanoni et al., 2016). Quorum-sensing bacteria suppress bacterial growth and biofilm development by disrupting bacterial communication (Lee et al., 2018; Yi et al., 2024). Whereas, enzymatic approaches can either hydrolyze biofilm components to prevent their formation or mechanically detach established biofilms (Figure 2; Ye et al., 2019; Li et al., 2021; Zanoni et al., 2016).

3.1 Customized antibiofouling polymers in hydrogels

Antibacterial polymers are widely used in the synthesis of anti-biofouling hydrogels due to their sustainability, ease of production, and broad availability. As summarized in Supplementary Table S2, various positively charged nitrogen-substituted polymers interact with negatively charged bacterial components inhibiting the biofouling on the surface of the material through electrostatic interactions. The presence of cationic charges on these polymer hydrogels is crucial for the antibacterial properties. Poly (imidazolium) (Wang J. et al., 2022) exhibited 99% antibiofouling performance within 1 h against *E. coli* (*Escherichia coli*) and *S. aureus* (*Staphylococcus aureus*). Chitosan, a cationic natural polymer with inherent amine functionality is a sustainable option (Li et al., 2022), has demonstrated 95% antibiofouling efficiency in a 15-day test (Supplementary Table S3; Li et al., 2022).

3.2 Antibiofouling hydrogels with microbial adhesion resistance and bactericidal properties

Biofouling occurs on hydrogel in two key steps: the initial adhesion of microorganisms to the surface of hydrogel and colonization after that (Roberts et al., 2012; AlSawaftah et al., 2022). Hence, antibiofouling mechanisms of hydrogels are primarily driven by two factors: improving resistance to microbial adhesion and delivering bactericidal effects through various physicochemical properties. One key mechanism of microbial adhesion resistance is the creation of a hydrophilic protection layer on the hydrogel's surface, which attracts water molecules, forming a layer of water on the surface of the material (Sójka et al., 2023; Zhang et al., 2018; Wibisono et al., 2015; Peng et al., 2022; Xu et al., 2023; Wen et al., 2021). This water layer acts as a barrier, preventing bacteria from adhering to the materials surface, thereby reducing biofilm and colony formation. Notably, combining cationic and hydrophilic functionalities strengthens electrostatic interactions with water while further enhancing microbial resistance (Wen et al., 2021; Zhou et al., 2019; Yang et al., 2018). These polymer hydrogels demonstrate strong antibacterial performance in water treatment applications. Polymers such as poly-sulfobetaine methacrylate (Sójka et al., 2023) and carboxybetaine acrylamide (Wen et al., 2021) facilitate the formation of a protective hydration layer, thereby preventing bacterial adhesion with 90%–96% effectiveness against *E. coli* (Supplementary Table S3; Li et al., 2022; Peng et al., 2022; Wen et al., 2021) This is further supported by studies showing hydrogels containing hydrophilic surfactants like benzalkonium chloride and dicocoalkyldimethyl ammonium chloride which have demonstrated extended fouling-free periods of 10–14 weeks in marine environments (Supplementary Table S3; Cowie et al., 2006)

3.3 Integration of nanoparticles into hydrogels for enhanced antibiofouling properties

Nanoparticles inhibit biofilm formation through biocidal ion release or ROS generation (Zhang et al., 2018; Baek et al., 2015; Wang J. et al., 2022; Guo et al., 2021). Silver nanoparticles (AgNPs) are widely studied for their antimicrobial and antibiofouling properties in water treatment (Baek et al., 2015), as hydrogels incorporating AgNPs release Ag^+ ions, which disrupt bacterial cell walls, proteins, and genetic material, leading to bacterial death. AgNPs have been shown to lyse approximately 80% of *E. coli* cells after prolonged exposure (Supplementary Table S3; Baek et al., 2015). However, AgNPs could induce oxidative stress in non-target organisms (Luoma SN, 2008; Asharani et al., 2008), disrupt microbial ecosystems essential for nutrient cycling (León-Silva et al., 2016), and contribute to antimicrobial resistance, posing public health risks (Luoma SN, 2008). To mitigate these risks, alternative antimicrobial nanoparticles have been explored. Saleque et al. (2023) Embedded tantalum telluride quantum dots in hydrogels has suppressed the growth of *S. aureus* and *E. coli* cultures by 26% and 34%, respectively through physical disrupting bacterial membranes and interference with deoxyribonucleic acid replication in bacteria (Supplementary Table S3). Additionally, graphene oxide nanosheets, when loaded onto zwitterionic polyampholyte hydrogels grafted onto ultrafiltration polyethersulfone membranes, led to an 80% reduction in *E. coli* colonies by combining biocidal activity with a hydrophilic protection layer (Supplementary Table S3; Zhang et al., 2018)

ROS-based mechanisms can further enhance the antibiofouling performance of hydrogel. ROS, such as hydrogen peroxide and hydroxyl radicals, disrupt bacterial membranes, proteins, and DNA. Quinone-modified activated carbon membranes, for example, generate ROS, achieving 99% bacterial inactivation within an hour while maintaining mechanical stability and preventing biofouling for up to 5 days (Supplementary Table S3; Guo et al., 2021) Despite these advancements, the toxicity of these nanoparticles remains largely unexplored for large-scale applications. Further research is needed to assess their biocompatibility and long-term environmental impact.

3.4 Antibiofouling hydrogels formation with sustainable approaches

Quorum-quenching bacteria and enzymes are considered effective and sustainable antibiofouling agents due to their natural origin and environmentally benign properties (Supplementary Table S3; Lee et al., 2018; Yi et al., 2024; Ye et al., 2019; Li et al., 2021; Zanoni et al., 2016) Hydrogels incorporating quorum-quenching bacteria have been shown to inhibit bacterial growth by disrupting quorum sensing, a critical bacterial communication system that regulates biofilm formation (Lee et al., 2018; Yi et al., 2024). Lee et al. (2018) embedded *Acinetobacter* sp. into hydrogels, which degraded AI-2 quorum-sensing molecules and reduced biofilm formation in *Aeromonas* sp., *Enterobacter* sp., *E. coli* K-12, and *B. subtilis* by 51%, 70%, 33%, and 33%, respectively. When encapsulated in membrane bioreactors, these hydrogels delayed biofouling and extended operational lifespan by 4.8 times. Similarly, Yi et al. (2024) developed microcapsules containing *Rhodococcus* sp. in a semi-interpenetrating hydrogel network, achieving over 99% quorum-sensing molecule degradation within 8 h and maintaining efficiency for 3 months. Enzyme-based antibiofouling hydrogels offer another assuring strategy. Li et al. (2021) designed a lysozyme-encapsulated hydrogel with a dual antibacterial mechanism: its negatively charged surface repelled bacteria to reduce adhesion, while it released lysozyme in response to acidic conditions or glutathione, breaking down bacterial cell walls. This system increased *E. coli* and *S. aureus* mortality by 85%. Ye et al. (2019) further improved lysozyme stability by immobilizing it within a hydrogel, enhancing temperature tolerance and retaining activity for 55 days. This porous hydrogel structure captured bacteria and catalyzed lysis, achieving 99.4% inhibition of *E. coli* within an hour and maintaining over 96% inhibition for 30 h. In another approach, Zanoni et al. (2016) functionalized silica nanobeads with Proteinase K, which physically disrupted *P. fluorescens* biofilms and enzymatically degraded their protein matrix. This method reduced biofilm coverage and thickness while preserving bacterial viability, offering an alternative to conventional bactericidal strategies. Integrating such quorum-quenching bacteria and enzymes into hydrogels not only enhances antibiofouling performance but also allows for material reuse by immobilizing active agents within a hydrated polymer network. Additionally, hydrogels can trap contaminants within their matrix, further improving antibacterial properties.

Despite these advantages, several trade-offs must be considered. Antibacterial nanoparticles, while effective, raise concerns about cytotoxicity and environmental impact due to the release of toxic ions that can disrupt microbial ecosystems and contribute to antimicrobial resistance. Additionally, while hydrophilic polymer coatings enhance biofouling resistance, they may compromise mechanical strength and long-term durability, limiting practical use. Quorum-quenching bacteria and enzyme-based approaches offer a sustainable alternative but present challenges related to stability, scalability, and potential loss of activity over time. Balancing efficacy, longevity, and environmental impact remains a key challenge in developing hydrogel-based water treatment materials.

4 Antibiofouling component modifications to improve short-chain PFAS removal

Unlike conventional water treatment materials with limited tunability, hydrogels offer customizable functionality, allowing their properties to be tailored for specific applications. By modifying surface functional groups to enhance both antibiofouling and short-chain PFAS removal, hydrogel-based materials can achieve high adsorption efficiency while preventing microbial growth, making them ideal for long-term water treatment (Figure 2). This approach includes incorporating positively charged or hydrophobic groups to facilitate short-chain PFAS adsorption, while also introducing additional functional elements that discourage microbial attachment and inhibit biofilm formation, ensuring sustained filtration performance (Wang P. et al., 2022; Chaix et al., 2024). For example, quaternary ammonium-modified hydrogels, which exhibit a strong binding affinity for short-chain PFAS due to robust electrostatic interactions (Ateia et al., 2019), and antimicrobial properties effectively disrupt bacterial membranes, making them highly effective against biofilm-forming microorganisms such as *E. coli* and *S. aureus* (Li et al., 2022; Peng et al., 2022; Chen et al., 2024). Predictably, the combination of quaternary ammonium and antibiofouling components in hydrogels demonstrate high effectiveness for short-chain PFAS removal for long term with resistance to biofouling.

Furthermore, these obtained materials can also be designed to optimize PFAS adsorption through size-exclusion mechanisms within porous adsorbents (Ateia et al., 2019). Advanced fabrication techniques such as 3D printing and electrospinning enable the development of hydrogels with intricate geometries and expanded surface areas, ultimately improving adsorption efficiency and long-term performance in water treatment applications (Chaix et al., 2024).

5 Challenges and future directions on antibiofouling hydrogel-based water treatment material for short-chain PFAS removal

Hydrogel-based materials have shown significant potential for short-chain PFAS removal and biofouling resistance in water

treatment applications. However, several challenges remain (Supplementary Table S1). First, further studies are needed to investigate the compatibility and performance of antibiofouling components integrated into hydrogels to enhance both short-chain PFAS removal and biofouling resistance (Figure 2). The performance of these hydrogels should be evaluated for antibacterial activity, biofouling resistance, and PFAS removal, with further data required to validate their long-term effectiveness in short-chain PFAS removal applications. This includes both advanced treatment processes for drinking water treatment and domestic water treatment products.

Moreover, hydrogel materials as emerging adsorbents are still under lab-scale study, therefore, more pilot-scale studies or full application studies are expected to further validate the performance of promising hydrogels. Unlike conventional adsorbents, which are highly commercialized, the cost of hydrogels for water treatment is still unknown. Finding more low-cost raw materials for hydrogel preparation have the potential to reduce production costs by utilizing bio-based materials and demonstrate promising scalability.

The engineering application of hydrogel adsorbents is limited by factors such as gel strength and degradation under extreme conditions. Further optimization is needed for field use, with the ability to be customized for both short- and long-chain PFAS. Additionally, the long-term effectiveness, environmental impact, and potential toxicity of these materials remain concerns, necessitating life cycle assessments to evaluate their full environmental footprint—from production to disposal—to ensure that their benefits outweigh any ecological risks before large-scale implementation (Verduzco and Wong, 2020). Future research should focus on enhancing the stability, selectivity, and environmental safety of hydrogel-based systems, as well as exploring advanced fabrication techniques and more sustainable material options to ensure their feasibility for large-scale water treatment applications. With ongoing research and optimization, hydrogel-based systems have significant potential to become a sustainable, efficient solution for addressing short-chain PFAS contamination in water, providing both enhanced performance and long-term applicability in real-world water treatment scenarios.

Author contributions

KD: Writing – original draft, Writing – review and editing, Visualization. GF: Writing – original draft, Writing – review and editing. IV: Writing – original draft, Writing – review and editing. SS: Writing – original draft. RP: Visualization, Writing – review and editing. RD: Writing – review and editing. YY: Writing – original draft, Funding acquisition, Project administration, Supervision, Visualization, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fceng.2025.1565754/full#supplementary-material

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