

How Do Novel PFAS Sorbents Fit into Current Engineering Paradigm?

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ABSTRACT: As the emergence of novel sorbents brings new possibilities for treatment of per- and polyfluoroalkyl substances (PFAS), drinking water and wastewater utilities face critical decisions in selecting effective, future-ready technologies. With regulatory pressures to address PFAS contamination mounting, however, many utilities may not be in a position to fully evaluate the potential of these novel sorbents and are instead preparing to adopt established technologies that are currently available, such as granular activated carbon (GAC) and ion exchange (IX) resins. Given the expected long life spans of any chosen system, it is important to consider all options, including future treatment innovations. This perspective provides insights into their potential advantages and challenges by exploring the current state of novel sorbents within the broader context of existing technologies. Novel sorbents bring promising benefits, including enhanced selectivity, rapid kinetics, and flexibility for different PFAS chemistries, particularly in challenging matrices such as wastewater. Despite their advantages, significant work remains to refine these materials for large-scale application, including addressing scalability, cost-effectiveness, fouling resistance, and regulatory certification hurdles. By examining key factors for both utilities and novel sorbent developers, this perspective aims to guide informed decisions that balance immediate regulatory compliance with long-term adaptability.

KEYWORDS: Novel adsorbents, PFAS, Engineering criteria, Cost, regulation



1. INTRODUCTION

In 2024, the U.S. Environmental Protection Agency (EPA) designated two per- and polyfluoroalkyl substance (PFAS) compounds, perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), along with their salts and structural isomers, as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).¹ In addition, EPA also established a National Primary Drinking Water Regulation under the Safe Drinking Water Act (SDWA) for PFOA, PFOS, and four additional compounds.² This new regulatory framework places considerable pressure on drinking water and wastewater utilities to implement effective PFAS treatment solutions. Many utilities are turning to well-established technologies, such as granular activated carbon (GAC) and strong-base anion exchange resins (IX), which rely primarily on hydrophobic and electrostatic interactions, respectively, for contaminant removal, and which have proven to adsorb and remove PFAS effectively.³ However, the increasingly complex demands of modern water treatment, driven by cost constraints, evolving regulations, and the need for multifunctional solutions, are fueling interest in novel sorbents.⁴ These

advanced materials promise substantial benefits, including selectivity for specific PFAS, higher adsorption capacities, faster kinetics, and easier regeneration without the need for harsh chemicals.⁵ Despite their potential, utilities must make critical infrastructure and treatment strategy decisions before the full operational readiness of these emerging technologies is confirmed.⁶ Furthermore, novel sorbents may be designed to address the removal of short-chain PFAS or other compounds that are poorly removed by conventional medias.⁷

As utilities navigate this rapidly evolving landscape, the potential of novel sorbents in water treatment continues to grow.^{8,9} These materials could significantly improve PFAS removal efficiency, providing a more targeted and potentially cost-effective alternative to conventional methods. Yet, there are several important outstanding questions: Are these

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sorbents scalable for widespread use? How will they perform long-term, and how do their costs compare with traditional methods? Moreover, integrating these technologies into existing treatment frameworks adds complexity, especially for utilities facing aging infrastructure and budgetary constraints.¹⁰ U.S. drinking water utilities face a significant compliance deadline for 2029 to PFAS monitoring and reporting by 2027 and meeting finished water MCLs by 2029. Though this deadline may seem distant, utilities must select treatment technologies, finalize engineering designs, and construct upgraded systems several years in advance. This tight timeline compels utilities to balance the advantages of novel sorbents with the risks of adopting a technology still proving its long-term viability.¹¹

In this Perspective, we focus specifically on municipal water and wastewater treatment plants, considering them collectively unless otherwise noted. These facilities are on the front lines of the PFAS challenge and will play a pivotal role in determining which technologies gain widespread adoption. As regulations tighten, integrating innovative sorbents into treatment processes could transform PFAS management. Our objectives are to (1) succinctly describe the novel aspects of main types of novel PFAS sorbents reported in the literature to date, (2) review the engineering paradigm (i.e., engineering principles and operational factors) that influence choices of technology implementation for PFAS removal, and (3) explore how novel sorbents can be adapted within the existing engineering paradigm of adsorptive technologies to offer effective, efficient, and sustainable PFAS removal. Realizing the full benefits of these materials will require overcoming substantial technical, economic, and operational hurdles to ensure their effective deployment in real-world scenarios. This work only focuses on adsorptive technologies and not comparing novel sorbents to other technologies like membranes or other separation techniques.

2. NOVEL SORBENTS

The pursuit of more efficient PFAS removal strategies has led to the development of novel sorbents with tailored properties to address the unique challenges of PFAS contamination in water treatment. Unlike conventional adsorbents, these materials leverage advanced design principles to enhance selectivity, kinetics, and capacity, offering promising alternatives in both municipal and industrial settings.¹² Novel sorbents combine a range of mechanisms to increase PFAS affinity and achieve faster adsorption kinetics, including electrostatic attraction, hydrophobic interactions,⁴ fluorophilic interactions,¹³ and optimized pore size and configurations.⁹ This multifunctional approach is critical in complex water matrices, where varying PFAS chemistries and the presence of other organic and inorganic compounds that act as foulants and competitors to removal sites can complicate removal processes. Though novel sorbents are not only explicitly being developed for PFAS treatment, but this paper also focuses on selective novel sorbents for PFAS because they are actively being developed to address regulatory compliance needs in the water sector. Moreover, they are being developed from a range of source materials. Notwithstanding, many of the concepts discussed in sections 3 and 4 would be applicable to non-PFAS novel sorbents.

Several advanced materials exemplify the diverse approaches being taken in novel sorbent design. Metal–organic frameworks (MOFs)¹⁴ or covalent organic frameworks (COFs),¹⁵

for instance, exhibit high surface areas and customizable pore sizes that facilitate rapid and selective PFAS adsorption. By fine-tuning the metal nodes and/or organic linkers, researchers have enhanced both the affinity and capacity of these materials for PFAS. Cyclodextrin-based sorbents represent a different structural approach by employing cyclic molecular cavities that can encapsulate PFAS molecules based on their size and shape.⁹ These sorbents use hydrophobic capture as a primary mechanism, allowing them to selectively isolate PFAS compounds, including smaller, short-chain PFAS that are often difficult to remove. Cyclodextrins' inherent biodegradability and nontoxic nature make them an attractive choice, and ongoing work is improving their regeneration potential, which is vital for long-term, sustainable use.¹⁶

Hydrogels and their fluorinated variants offer a flexible platform for PFAS removal due to their water-swollen polymer structures.¹⁷ Fluorinated hydrogels, in particular, demonstrate a unique affinity for PFAS through fluorophilic interactions, closely mirroring the fluorinated nature of PFAS compounds themselves.¹⁸ This similarity enhances their binding efficacy and allows them to remove a wide range of PFAS, including both long- and short-chain molecules.^{18,19} Hydrogels also provide the benefit of being regenerable, which helps maintain cost-effectiveness and reduces chemical waste.²⁰ Surface-modified clays, meanwhile, build on naturally occurring high surface area and stability. By modifying clay surfaces with functional groups that attract PFAS molecules, researchers have developed a low-cost, accessible solution with promising adsorption efficiencies.^{21,22} Although clays may lack some of the high-capacity features of engineered materials like MOFs, their affordability and scalability make them practical choices.²¹ The higher density of clays relative to synthetic organic sorbents also represents a competitive advantage toward potential backwashing operations to remove solids as a higher density would enable greater backwashing velocities without washing media out of contactors.

Together, these novel sorbents exhibit a range of structural and chemical strategies that contribute to faster adsorption kinetics and higher PFAS removal efficiencies across complex water matrices. The key to their enhanced performance lies in designing a balanced interplay of different mechanisms that collectively drive a high affinity for PFAS compounds.⁴ While each material offers distinct advantages and limitations, they all reflect a movement toward more selective, sustainable, and scalable PFAS treatment options. The potential of these novel sorbents to reshape PFAS treatment technologies is substantial, but real-world applications will ultimately depend on their ability to maintain stability, cost-efficiency, and effectiveness across diverse operating conditions.

3. CURRENT ENGINEERING PARADIGM

In water treatment, technology adoption and design decisions involve a complex balance of performance, cost, and operational fit. Utilities prioritize not only capital and operational expenses but also the compatibility of new systems with existing infrastructure, regulatory compliance, successful performance in comparable applications, potential longevity of the vendor for media replacement and support, and downstream impacts on water quality. Each new technology, including novel sorbents, must meet these rigorous standards while avoiding unintended consequences that could disrupt established treatment practices (e.g., impacts on disinfection, corrosion, or taste and odor issues). The design of sorbent-

based treatment systems, whether incorporating conventional or novel adsorptive media, hinges on key operational parameters that govern efficiency and scalability. Given the extended operational life spans expected of water treatment installations, which span decades, informed decision-making is essential. This section examines the core engineering principles and operational factors that influence technology choices, with a focus on the parameters shaping the potential role of novel sorbents in drinking and wastewater treatment. Contactor design and operation also are critical to maintaining proper flow distribution. While these elements are presented individually, successful implementation of adsorbents in water treatment will require a holistic consideration of these factors.

3.1. System Design. **3.1.1. Surface Loading Rate (SLR).** SLR is central to optimizing media performance, as it determines the rate at which water flows through the sorbent bed. The maximum SLR determines the minimum footprint necessary for media beds. Operating at the right SLR is also critical for ensuring that the media effectively adsorbs target contaminants without channeling, which can cause uneven flow and short-circuiting.²³ GAC filters are typically operated at 2–10 GPM/ft², while IX filters may be operated at higher SLRs of 6–18 GPM/ft².²⁴ Although higher SLRs can reduce the thickness of the film layer around adsorbents beads, leading to more efficient external mass transfer, without adequate column depth it can lead to incipient breakthrough and poor increasing contaminant removal. However, high SLRs can result in bed shifting causing short-circuiting, or bed compaction leading to high head loss and reduced EBCT. Novel sorbents, similar to IX systems, are generally expected to operate at higher SLRs than GAC, which translates to smaller required cross-sectional areas, and therefore more compact, and smaller footprint installations.²⁵

3.1.2. EBCT and Media Depth. Another essential factor is empty bed contact time (EBCT), a measure of the amount of time the water is in contact with the media, calculated as the ratio of the bed volume and the treatment flow rate. Optimal EBCT varies across media types; novel sorbents and IX resins for PFAS removal typically perform efficiently at lower EBCTs (2 to 5 min), whereas GAC beds for PFAS removal are being designed with longer EBCTs (10 to 30 min).^{24,26} Adjusting SLR and EBCT parameters allows engineers to balance media depth, pressure drop or head loss, and system height, providing a design framework that accommodates practical constraints like media expansion during backwash, building height limits, and maintenance access.^{25,27}

3.1.3. Commercial Contactors and Underdrains. GAC, IX, and many novel sorbents can be implemented using commercially available pressure vessel contactors and standardized sizing options that simplify system design, helping to reduce both customization requirements and costs. For novel sorbents in particular, leveraging standardized systems enables consistent performance data collection, which can guide design decisions and accelerate their adoption by ensuring predictable, reliable treatment outcomes. Underdrains are also essential for collecting treated water and preventing media displacement, and thus they add an additional layer of design complexity, affecting both structural requirements and system configuration.²⁸

3.2. Impacts on and from Water Quality. **3.2.1. Chlorine Tolerance and Consumption.** Novel sorbents, like traditional materials, must function within diverse water chemistries that can affect both the media's efficacy and broader water quality.

For example, chlorination is widely used to meet disinfection targets in finished drinking water and disinfect wastewater before it is discharged back into the environment. Chlorine tolerance, however, varies significantly among adsorbents. Although it is sometimes used for dechlorination purposes, chlorine consumption by GAC is not ideal in a drinking water facility due to need to re-chlorinate the GAC effluent to maintain a distribution system residual. Because GAC also removes disinfection byproduct precursors and this is desired before chlorination, chlorination is rarely practiced ahead of GAC treatment. IX resins and novel sorbents also quench chlorine residuals, but the exposure to chlorine harms the media. Therefore, when chlorine is present, prequenching of chlorine is needed prior to IX treatment to avoid media degradation. Gel-type IX resins are particularly vulnerable due to the low cross-linking of their polystyrene-divinylbenzene backbones, whereas macroporous resins exhibit better tolerance, albeit with potential reductions in functional group integrity over time.²⁹ Chlorine or other oxidant exposure will destroy gel IX resins, breaking down the resin backbone and potentially forming nitrosamines, such as *N*-nitrosodimethylamine (NDMA). Chlorinated resins will become gelatinous, requiring immediate replacement.

3.2.2. Competing Co-occurring Constituents. Co-occurring water constituents, including natural organic matter (NOM) and common anions (e.g., chloride, sulfate, nitrate), can substantially influence the performance of adsorptive media. NOM can compete for GAC and IX resin adsorption sites,^{30,31} and also generally foul the media,³² reducing access to active sites and pore spaces essential for effective PFAS binding. This fouling effect is a major consideration in sorbent design, as higher NOM levels are correlated with reduced adsorbent efficiency. Additionally, the presence of anions impacts GAC and IX resin capacity and selectivity for PFAS, with higher ionic strengths commonly leading to lower PFAS removal efficiency.^{33–35} The presence of anthropogenic compounds such as pesticides or pharmaceuticals may further influence bed life, as these compounds can preferentially adsorb onto the media, accelerating the need for replacement or regeneration. Surfactants can also coat sorbents, limiting mass transfer.

3.2.3. Corrosion Implications. Treatment choices will have downstream system impacts on distribution system corrosion. Therefore, the expected effluent water quality will need to be evaluated, as changes to water chemistry can destabilize established corrosion scales within distribution systems. Adsorptive technologies that remove NOM can facilitate disinfectant stability creating a stable oxidation potential that is conducive to stable distribution-system scales. Stable disinfectant residuals can also mitigate microbially induced corrosion. Conversely, technologies that alter pH, ionic composition, or buffering capacity may disturb existing scales, potentially accelerating corrosion and complicating compliance with lead and copper rules. Unbuffered ion exchange resins can temporarily depress pH, particularly in low-alkalinity waters and increase while chloride while reducing sulfate (changing the chloride-sulfate-mass-ratio); buffered resins have been developed to reduce pH changes at startup. This interplay between treatment effects and distribution system stability is a key consideration in the evaluation of new media.

3.3. Regulatory and Financial Considerations. **3.3.1. Media Usage Rate.** The operational life and efficiency of adsorptive media depend on factors such as media usage



Figure 1. Major consideration of system design, water quality impacts, operational demands, and regulatory requirements for integrating novel adsorbents into current engineering paradigm.

rate (MUR) and the ability to regenerate spent media. MUR, a measure of the media required to treat a specific water volume, directly impacts operation and maintenance (O&M) costs. High MURs indicate shorter bed lives and frequent replacements, whereas lower MURs, or higher bed volumes treated per replacement, help to minimize expenses, and improve operational sustainability. Media with high selectivity or capacity for target compounds would be expected to generally exhibit lower MURs, translating into reduced costs for utilities.

3.3.2. Regenerability and Subsequent Residual Streams. Regenerability represents another important operational factor. While some GAC systems allow for off-site thermal regeneration at specialized facilities,³⁶ restoring adsorptive capacity with a minimal replacement percentage, most PFAS-selective IX resins currently lack viable regeneration options for drinking water applications.³⁷ This limitation often necessitates the disposal of spent resins, raising concerns over environmental impact and disposal costs. In contrast, novel sorbents with regeneration capabilities, could offer utilities a more sustainable alternative if regeneration can be completed without toxic, hazardous, or difficult to handle regenerants while also maintaining PFAS selectivity and adsorption efficiency post regeneration.^{4,5,38}

3.3.3. Permitting. Permitting and certification processes are critical in the adoption of any new treatment technology, particularly those intended for drinking water applications. In the U.S., most utilities must obtain permits prior to installing treatment systems, requiring compliance with both national and local regulations. Local permitting authorities consider factors like media composition and expected effluent quality, which can complicate efforts to generalize design guidelines or media applicability across regions. Permits are granted based on performance data from pilot systems or full-scale installations that demonstrate the technology's effectiveness, safety, and compatibility with regulatory standards. For drinking water applications, this often involves stringent testing to ensure that new treatment technologies do not introduce harmful byproducts, negatively impact water quality, or interfere with existing treatment processes.

3.3.4. Existing Certification. In addition, certification standards play a significant role, with 49 of the 50 states requiring NSF/ANSI 61 certification for materials used in

drinking water systems.³⁹ This certification provides some assurance that materials do not leach harmful contaminants into drinking water. However, obtaining NSF 61 certification can be challenging for novel sorbents in early development, as the certification process is closely tied to specific manufacturing facilities and material compositions. Minor adjustments in sorbent chemistry or change in manufacturing site to e.g. enable production of larger sorbent volumes may necessitate recertification, a process that could delay the market readiness of these materials. Wastewater systems are generally exempt from NSF 61 requirements, offering greater flexibility in the deployment of experimental or novel sorbents within these contexts.

4. WHERE DO NOVEL SORBENTS FIT IN THE CURRENT ENGINEERING PARADIGM?

As water treatment systems evolve to meet growing regulatory and environmental demands, the unique properties of novel sorbents make them promising candidates for addressing persistent contaminants like PFAS.⁴⁰ These advanced materials offer distinct advantages, such as tunable chemical structures and enhanced adsorption kinetics, which position them as potential improvements over conventional technologies. However, integrating novel sorbents requires careful consideration of system design, water quality impacts, operational demands, and regulatory requirements (Figure 1). Water treatment technologies will all be judged against the same treatment objectives or ability to support regulatory compliance, but it is important to understand how characteristics of novel sorbents impact their ability to meet those objectives

4.1. System Design. **4.1.1. Tunability and Capacity.** One of the defining features of novel sorbents is their tunability. The chemical composition and surface properties of some materials can be customized at the molecular level, enabling specific sorption mechanisms, both nonexchange and ion-exchange, that enhance PFAS selectivity.⁴⁰ Studies have demonstrated that adjusting chemical moieties on novel sorbent surfaces allows for controlled interactions with target compounds, an essential feature for optimizing sorbent performance in varied water matrices. This tunability enables novel sorbents to be tailored for either broad-spectrum PFAS capture or focused removal of specific PFAS types, giving

utilities flexibility in addressing different contamination profiles. Further, the superior selectivity of novel sorbents contributes to their greater effective capacity for PFAS removal compared to commercial sorbents, which enables their operation at similar, and potentially greater, SRLs than those of ion-exchange resins. The greater capacities and SLRs translate into reduced footprint design for PFAS removal systems.

4.1.2. Kinetics. The superior tunability of novel sorbents is also exploited in terms of PFAS removal kinetics. A significant advantage of novel sorbents lies in their fast adsorption kinetics, which facilitate efficient PFAS capture at shorter EBCT, similar to those of IX systems.²⁶ These faster kinetics and lower EBCT translate into lesser packed-bed depth requirements. The combination of lower packed-bed depth requirements and ability to operate at higher SLRs lead to compact system designs, reducing the space and infrastructure required to achieve effective treatment. This efficiency is particularly advantageous when space constraints or cost limitations are major considerations in system planning. Faster kinetics will also result in sharper breakthrough profiles that can allow for more efficient media usage depending on design and treatment goals. Sharp breakthrough curves from fast kinetics, however, may carry the practical disadvantage of “sudden” exceedances of target PFAS concentrations in the effluent water. This could be potentially managed by lead-lag system designs.

4.1.3. Non-Packed Bed Applications. The applicability of novel sorbents may also be expanded by non-packed bed applications. While packed beds are ideal for low-competition, low-fouling conditions like drinking water, the higher fouling and competitive adsorption environment of wastewater can reduce packed bed performance. Fluidized sorbent contactors, though underutilized at municipal scales, represent a potential avenue for integrating novel sorbents in high-competition matrices. Tailoring novel sorbents (e.g., particle size) to fluidized or other non-packed bed configurations could make them viable in challenging settings where fouling potential and fluctuating PFAS concentrations are common.

4.1.4. Durability. Another practical consideration about media selection or use is durability. Only materials capable of withstanding the mechanical stresses of transport, handling, and operational demands (e.g., backwashing and media replacement) are likely to be adopted widely. Novel sorbents must demonstrate resilience under these conditions to avoid breakdown or abrasion, which can produce fines, leading to head loss and compromised performance. Future larger-scale testing, including further lab-scale and pilot testing, should evaluate the durability of these sorbents under real-world stressors (e.g., fluidization for backwashing) to ensure their stability and practicality in full-scale systems.

4.1.5. Grain Size Distribution. Grain size distribution is critical in packed-bed configurations, where the uniformity of particle sizes affects head loss and hydraulic resistance. Novel sorbents produced for full-scale implementation must have grain size (distributions) suitable for the intended SLRs, a key determinant of head loss.²⁶ Given that novel sorbents are in the development stage, there is the opportunity to design them with optimized grain size distributions that can provide predictable hydraulic performance, balancing efficient flow with maximum contaminant contact. By producing tailored grain sizes, novel sorbents could potentially match or even

surpass the flow efficiencies of conventional materials, allowing for smoother integration into existing system designs.

4.1.6. Order of Unit Operations. Water treatment facilities can range from very simple, with only one- or two-unit operations, to very complex, with numerous steps. The placement of an adsorber will be dictated by many factors, but its performance can be tied to both how and where it is installed. Many unit operations for PFAS removal are near the end of the treatment train because most unit operations do not remove much PFAS, and pretreatment can improve downstream adsorber performance by removing foulants and competing sorbates such as NOM and inorganic anions. Upstream process steps like pH adjustment, particulate removal (sand filter or low-pressure membranes), disinfection, oxidation, air-stripping or others can impact the performance of current media and must be considered as part of a design process for novel sorbents. Novel sorbents in the literature have not been shown to have properties that would enable placing them in a different location from GAC or IX resins in a water treatment-train. However, if novel sorbents are shown to or developed to tolerate a wide range of pH or disinfectants, they may allow utilities to be more flexible in the design of their treatment-trains.

4.2. Impacts on and from Water Quality. Novel sorbents enhance PFAS removal but may not remove co-contaminants, unlike broad-spectrum adsorbents like GAC. For most water systems that are already meeting existing non-PFAS regulations and water quality goals, PFAS-specificity may be highly desirable. However, if an adsorbent is overly selective then it may not adequately address other constituents in the water. In water treatment, a broader spectrum adsorbent may be desirable to remove both PFAS and other chemicals of concern. In drinking water applications, the co-removal of other constituents such as other regulated contaminants, disinfection byproduct precursors, and taste and odor compounds can be beneficial, and in some cases necessary, to the successful operation of the plant. In wastewater treatment, broad-spectrum adsorbents have a more difficult balance to strike because although removal of NOM and competing ions can be beneficial, it would also significantly reduce the performance of the media for PFAS due to the substantially greater concentration of co-constituents as compared to drinking water sources. Conventional adsorbents, such as powdered activated carbon (PAC) used in drinking water and wastewater systems, similarly offer broader removal and may be preferable in complex matrices. Balancing selectivity, co-contaminant removal, and feasibility depending on site-specific needs is key when evaluating novel sorbents for practical applications.

4.2.1. Competitive Desorption. The performance of novel sorbents is closely tied to their interactions within complex water matrices. A notable challenge for the removal of PFAS as a contaminant class is competitive desorption, particularly for short-chain PFAS and carboxylic acids, which tend to break through media faster than their long-chain and sulfonic acid counterparts. The disparate breakthrough time for different PFAS in the same water may cause previously adsorbed PFAS that breakthrough earlier to desorb in chromatographic fashion, leading to corresponding PFAS concentrations in effluent greater than those in the influent. The tunability of novel sorbents opens up the opportunity to develop sorbents with greater binding stability for PFAS that break through earlier (e.g., short-chain PFAS) which will be critical to

minimizing desorption risks, enhancing both efficiency and reliability.

4.2.2. Selectivity and Resistance to Fouling. Selectivity is another valuable trait of novel sorbents, which can be engineered to prioritize certain PFAS classes over other water matrix components. Such tunability of selectivity facilitates development of novel sorbents tailored to specific applications/PFAS profiles. High selectivity not only improves PFAS removal but also allows sorbents to maintain capacity under challenging conditions, including the presence of NOM and competing anions. However, selectivity alone may not suffice; sorbents must also resist fouling from NOM, which varies in composition and concentration across water sources and may represent the greatest threat to satisfactory sorbent performance in wastewaters. Further, iron and manganese are prevalent in both surface and groundwaters and have the potential to foul sorbents with a low-permeability metallic layer. Novel sorbents with enhanced fouling resistance and selectivity could become pivotal tools, especially if they can consistently capture target PFAS in environments rich in NOM and other potential foulants.

4.2.3. Regenerability. The ability to reuse or regenerate a material may play an important role in reducing the life-cycle costs of these media. Studies have shown that some novel sorbents can be regenerated, though it remains unproven whether the same regeneration protocols can be practically used at full-scale or the financial implications of these protocols. A lifecycle analysis comparing PFAS removal by (i) regenerable, nonspecific IX resins, (ii) landfill of PFAS-specific IX resins, and (iii) solvent-based regeneration of PFAS-specific IX resins estimated the latter to have the lowest financial cost and environmental impact.⁴¹ Existing sorbents for municipal and other applications are often single-use sorbents: after they are saturated with PFAS they need to be disposed of as waste (e.g., in landfills) or incinerated. Potential future designation as hazardous waste would further increase the cost and complexity of spent sorbent disposal.⁴² Some activated carbons may be “reactivated” which involves subjecting the carbon to a thermal process similar to that used to produce new activated carbon. The reactivation process, however, needs to be performed in specialized facilities, with the cost of reactivated carbon being ~85% that of virgin carbon. Developing novel sorbents that can be regenerated after saturation so that they can be reused multiple times would contribute to lower cost of technology ownership. In-situ regeneration would be ideal, but off-site regeneration could also be beneficial.

4.3. Regulatory and Financial Considerations.

4.3.1. Certification Requirements. Not all water treatment applications will require certification, but it is important to consider how certification may impact adoption. One key consideration is how tunability will translate to final commercially available products. Current media manufacturers already market multiple lines of media for different applications. Multiple variants of novel sorbents may be required to identify them for their end uses, selectivity or other properties. While many current reports of novel sorbents discuss tunability, these may simply become different products rather than site-specific tuned sorbents. To streamline adoption, developers of novel adsorbents may need to work closely with regulatory bodies early in the development phase, ensuring that their materials meet both broad national standards and specific local requirements (Box 1). This

Box 1. Examples for State-Specific Certification Standards for Novel Sorbents

In the U.S., state-specific certification requirements for water treatment media significantly impact the adoption of novel sorbents. California and New York exemplify states with more stringent standards, especially for drinking water applications. Both require NSF/ANSI 61 certification for potable systems to prevent harmful chemical leaching. California’s State Water Resources Control Board mandates third-party testing and often requires in-state pilot testing to verify compliance with strict health standards. Similarly, New York’s Department of Health enforces high criteria, particularly for media impacting groundwater, making it challenging for novel adsorbents with variable formulations to secure certification.^{43,44}

Conversely, Texas and Florida adopt more flexible regulatory approaches, especially for nonpotable and industrial applications. While both states recognize NSF/ANSI 61 certification for drinking water, they allow noncertified media in nonpotable contexts to facilitate faster adoption and reduced certification costs. For example, the Texas Commission on Environmental Quality (TCEQ) allows certain technologies based on third-party data provided basic safety standards are met. Similarly, Florida allows more rapid piloting and adoption of novel sorbents for industrial uses, though utilities must monitor these systems to maintain water quality compliance.^{45,46}

Ohio and Pennsylvania strike a middle ground. Though they require NSF/ANSI 61 certification for drinking water, they also offer conditional approvals for pilot testing. Ohio permits temporary certification for district-specific trials to help utilities gather local performance data. Pennsylvania offers similar options, particularly in high-demand regions, allowing controlled pilot deployments before full certification.^{47,48}

These varied approaches illustrate the complexities developers face in the U.S. market. While the more stringent states like California and New York ensure high public health protection, their requirements can slow innovation. States like Texas and Florida promote faster adoption, especially for industrial uses, but may require extra diligence from utilities to maintain long-term compliance. For developers, understanding these regulatory nuances early can help streamline certification and facilitate responsible, widespread deployment of novel adsorbents across diverse regulatory environments.

proactive approach can help accelerate the deployment of innovative treatment technologies, ultimately supporting public health protection and environmental sustainability across diverse water systems.

4.3.2. Media Usage Rate. As discussed earlier, MUR reflects the amount of sorbent required to treat a specific water volume and is thus a key driver of O&M costs. For novel sorbents to gain traction, they must demonstrate competitive MURs or show substantial treatment longevity, enabling utilities to achieve cost-effective treatment goals. MURs competitive and/or greater than those of IX resins appear achievable given the reported superior kinetics and capacities of novel sorbents. Ongoing studies at bench and—importantly—pilot scale that benchmark novel sorbents against GAC or IX performance are essential for translating laboratory findings into actionable data for utilities. Additionally, understanding how MUR and

capacity translate into overall O&M costs is necessary for informed decision-making in the long term.

4.3.3. Affordability of Novel Sorbents. One of the key challenges in evaluating the role of novel sorbents in water treatment is determining their overall cost-effectiveness. While some sorbents are already being produced at commercial scales with well-established price points, many others are still in the research or early development stages, making their cost projections uncertain. For these new materials to gain widespread adoption, developers must identify a price threshold that meets the cost-benefit expectations of utilities. Factoring in the ongoing costs of replacing or regenerating media is also particularly important for evaluating the overall cost-effectiveness of novel sorbents as O&M costs can significantly impact long-term operational budgets. Furthermore, the ability of novel sorbents to be designed with high selectivity for certain chemicals may help treat water that would otherwise be challenging to treat, where the MUR and associated costs may be ultimately lower than for a more conventional adsorptive media. In this way, the direct media costs comparison between conventional and novel sorbents is not as simple as comparing cost per mass of these media. To be economically competitive, novel sorbents must have a similar or lower cost per volume treated than conventional sorbents. The cost per volume treated (e.g., \$/MG or \$/ML) metric accounts for both bed volumes treated and unit cost.

A further complication is the limited funding opportunities for novel sorbents. Although the Drinking Water State Revolving Fund (DWSRF) provides financial support for PFAS-related projects—including equipment purchases, treatment plant construction, and expansions—this funding is restricted to technologies recognized as the Best Available Technology (BAT). Since novel sorbents have not yet received BAT designation, they are ineligible for DWSRF funding, making it harder for utilities to justify the investment in unproven, though potentially more effective, solutions. This limitation presents a significant barrier to the adoption of innovative sorbents, even if they offer promising performance advantages over existing technologies.

5. ENVIRONMENTAL IMPLICATIONS

The emergence of novel sorbents offers water utilities an innovative approach to PFAS treatment that goes beyond the capabilities of traditional technologies. With recent regulatory pressures, utilities need flexible and effective solutions. Novel sorbents, with their tunable chemistries and fast adsorption kinetics, provide these advantages, but turning lab successes into field-ready solutions requires addressing technical, economic, and regulatory challenges. A key strength of novel sorbents is their tunability. By adjusting structure and chemistry, these materials can target specific PFAS types or be tailored to different water conditions, offering faster kinetics and higher capacities in compact designs. However, demonstrating their resilience against real-world variables—such as fluctuating PFAS levels, fouling agents, and competing organic matter—remains essential. Large-scale pilot studies will be crucial to confirm their suitability across diverse water treatment contexts.

Economic considerations are equally important. Despite their high efficiency, the current costs of novel sorbents may limit adoption. The economic viability of novel sorbents will be determined by media longevity, regeneration potential, and disposal requirements, in comparison with GAC and IX.

Transparent cost-benefit analyses will be essential for utilities to make informed choices that balance performance with affordability. Manufacturers must develop business models that enable recovery of facility capital costs while remaining cost competitive with established technologies that have existing manufacturing facilities. Regulatory readiness also plays a significant role. To be viable in drinking water applications, novel sorbents must meet rigorous standards like NSF/ANSI 61. This need for consistency poses a challenge for tunable materials, requiring a balance between customization and compliance. Early engagement with regulatory bodies will streamline certification and build trust in these technologies.

Successfully implementing novel sorbents will require interdisciplinary collaboration. Chemists, engineers, regulatory experts, and environmental scientists must address open questions around performance, environmental impacts, and sustainability. Life-cycle assessments (LCAs) comparing novel and conventional media will provide utilities with critical data to support both treatment effectiveness and environmental responsibility. Timely implementation of novel sorbents may require collaborative frameworks involving government, industry, and/or academia. In summary, novel sorbents have the potential to reshape PFAS treatment but achieving this will require technical validation, economic feasibility, and regulatory alignment. Through continued interdisciplinary collaboration, these materials can transition from promising concepts to essential tools in water treatment, safeguarding public health and environmental quality for the future.

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Notes

The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the Agency. Any mention of trade names, products, or services does not imply an endorsement by the Agency. The Agency does not endorse any commercial products, services, or enterprises.

The authors declare no competing financial interest.

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Jonathan Burkhardt is an environmental engineer with US EPA's Office of Research and Development. He received his PhD, MS, and BS in chemical engineering from the University of Cincinnati. His current research focuses include understanding the effectiveness of adsorptive technologies for treating drinking water and water quality changes within water distribution systems and premise plumbing systems.



Dr. Mohamed (Moha) Ateia Ibrahim is Group Leader with the United States Environmental Protection Agency (U.S. EPA), Office of Research and Development (ORD). Moha combines his expertise in environmental chemistry and materials chemistry to develop and evaluate innovative water treatment technologies to remove and/or degrade emerging contaminants, such as PFAS and microplastics. In parallel, Moha has initiated and is currently leading a multiagencies project to evaluate the environmental impacts of PFAS-replacement chemicals and formulations in fire fighting foams and consumer products. He is a member of the Weapons Systems and Platforms Technical Committee of fluorine-free foams (F3) for the U.S.

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