

Cross-national challenges and strategies for PFAS regulatory compliance in water infrastructure

Received: 19 April 2023

Accepted: 30 October 2023

Published online: 15 December 2023

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Per- and polyfluoroalkyl substances (PFAS) are notable health concerns, leading to global drinking-water regulations for primary PFAS. However, conventional drinking-water treatment methods are ineffective in eliminating PFAS due to their resistance to such processes. Moreover, certain disinfection procedures may inadvertently generate perfluorinated compounds from polyfluorinated precursor compounds. With evolving regulations, there exists an immediate demand for both technical and non-technical solutions that water treatment facilities can adopt. Here, to address this critical gap, we examine the primary challenges tied to PFAS removal and introduce a detailed four-stage protocol. We advocate for non-technical strategies to improve PFAS removal practices. The treatment trains and management recommendations presented in this Perspective are also geared towards helping utilities comply with regulations concerning other chemical contaminants, including disinfection by-products. We emphasize the necessity for practical PFAS monitoring and treatment guidelines and encourage utilities to leverage all available resources, to positively impact public health through improved water quality.

The Safe Drinking Water Act (SDWA) was enacted as US federal law in 1974, granting the US Environmental Protection Agency (US EPA) the authority to establish enforceable water-quality standards or maximum contaminant levels (MCLs) for contaminants of concern. Under the 1996 amendments to the SDWA, the US EPA must decide whether to regulate at least five previously unregulated contaminants every five years. Only 94 contaminants have been regulated under SDWA in the past 47 years (Fig. 1).

On 14 March 2023, the US EPA released a proposed national primary drinking-water regulation aimed at establishing federal MCLs of 4 ng l⁻¹ for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), along with a hazard index of 1.0 for a mixture

of four additional per- and polyfluoroalkyl substances (PFAS), perfluorononanoic acid (PFNA), hexafluoropropylene oxide dimer acid (HFPO-DA, commonly known as GenX chemicals), perfluorohexane sulfonic acid (PFHxS) and perfluorobutane sulfonic acid (PFBS). These chemicals are part of the PFAS family, a vast group of synthetic organic chemicals. Specifically, PFOA and PFOS have been detected in human blood samples worldwide at concentrations that pose risks to human health^{1–7}. In the United States, PFOA and PFOS were detected in >95% of blood samples tested during national surveys, with concentrations higher than other xenobiotic organic compounds such as disinfection by-products (DBPs)⁸. Several states in the United States have either completed or are in the process of finalizing state MCLs for PFAS in

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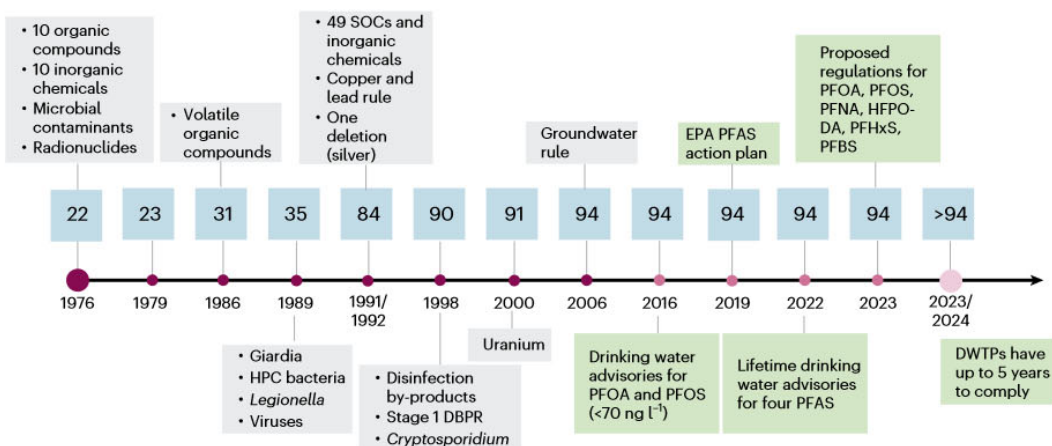


Fig. 1 | The number of contaminants (cumulative) regulated under the US SDWA. Timeline of cumulative contaminant regulations under the US SDWA, detailing the incremental inclusion of various contaminant groups such as organic, inorganic, and microbial contaminants from 1974 onwards, with an emphasis on recent developments in regulating PFAS substances. HPC,

heterotrophic plate count, which is a procedure for estimating the number of live, culturable bacteria in water and is used as an indicator of general bacteriological water quality. DBPR, disinfectants and disinfection byproducts rule, a set of regulations to protect drinking water from harmful disinfectants and their byproducts.

drinking water^{9,10}. Approximately 2,000 and 3,400 public water systems in the United States have mean concentrations of PFOA and PFOS exceeding the proposed federal MCLs (for example, 4 ng l⁻¹ for both PFOA and PFOS)¹¹.

Similar to the United States, many countries and regions worldwide have developed guidelines for PFAS in drinking water. In the European Union, for instance, the updated Drinking Water Directive recommends limits of 100 ng l⁻¹ for the combined total of 20 PFAS, including PFOA and PFOS¹². In addition, it suggests a 500 ng l⁻¹ limit for the sum of all PFAS¹². In Canada, the maximum acceptable concentrations for PFOA and PFOS are 200 ng l⁻¹ and 600 ng l⁻¹, respectively^{13,14}. The latest version of Chinese drinking-water standards stipulates maximum acceptable limits of 80 ng l⁻¹ for PFOA and 40 ng l⁻¹ for PFOS¹⁵.

Drinking-water standards for PFAS will markedly influence water utilities' compliance and operational requirements, as well as the assessment and communication of risk to the public. Once these PFAS regulations are finalized, public water systems in the affected countries must monitor and mitigate PFAS contamination in drinking water. A pressing challenge for drinking-water treatment plants (DWTPs) is preparing to meet these stringent PFAS standards.

Primary PFAS, such as PFOA and PFOS, are non-volatile at room temperature, ionic at circumneutral pH and amphiphilic. These physicochemical properties render them difficult to remove from water using conventional drinking-water treatment processes designed for removing suspended and colloidal particles, natural organic matter (NOM) and pathogens^{16–19}. Over the years, many non-conventional PFAS treatment technologies have been developed, including B₁₂-mediated reduction²⁰, photodegradation^{21–24}, electrochemical approaches^{25–27} and reductive defluorination^{28–32}. Although some of these processes have shown success in laboratory-scale experiments, most present considerable economic and design hurdles when scaled up for broader applications.

As regulations on PFAS levels in drinking water become increasingly stringent, water treatment facilities face growing pressure to adapt and comply. There is a notable gap in the literature, however, that provides actionable, comprehensive strategies tailored for these facilities to meet the evolving standards. In the first part of this Perspective, we outline the primary challenges associated with removing PFAS from water in full-scale DWTPs. Although each of these challenges may be worthy of extensive review and discussion^{33–35}, such a comprehensive

analysis is beyond the scope of this paper. Instead, we focus on summarizing the nature and importance of each challenge, rather than providing an extensive review of the state-of-the-art knowledge. An important goal in identifying these challenges is to develop solutions for reducing PFAS in drinking water to minimize human health risks. In the second part of this Perspective, we introduce technical and non-technical suggestions to ensure regulatory compliance. We propose a multi-barrier treatment train that allows for the targeted treatment that PFAS requires, while also providing a comprehensive solution for a range of other contaminants that are typically present in contaminated water supplies.

Challenges in removing PFAS in full-scale DWTPs

Outdated water infrastructure

Conventional drinking-water treatment processes, such as coagulation, flocculation, sedimentation, sand filtration and disinfection, are used worldwide (Table 1). Numerous studies have shown that these conventional techniques are ineffective at removing PFAS from drinking-water supplies¹⁸.

Efficient removal of PFAS from water at pilot and full scales can be accomplished through the use of materials such as granular activated carbon (GAC)^{18,36–39} and ion exchange (IX)^{18,40–43}, as well as through high-pressure membrane filtration⁴³ (Table 1 and Box 1). However, these enhanced techniques are not enforceable treatment techniques, meaning that most public water systems may not have them available to address PFAS-related compliance issues. Incorporating these techniques into existing treatment systems may necessitate additional space, energy and maintenance, which should be taken into consideration. In addition, careful planning and testing are necessary to ensure that the new processes integrate well with the existing system without compromising performance.

Precursor compounds

Previous research on the fate and removal of PFAS during water treatment has primarily focused on perfluorinated compounds. However, since 2012, the identification of numerous polyfluoroalkyl compounds, also known as precursor compounds, has expanded our understanding^{44–52}. These compounds have a similar structure to perfluoroalkyl compounds but feature a non-fluorinated moiety attached to the perfluorinated chain. Precursors comprise a substantial fraction of

Table 1 | Commercially available technologies for removal of water contaminants

Contaminant categories	Federal MCL	Clar. + GMF	Chlorination	Ozonation	GAC	IX	NF/RO
Total coliforms	5%	▲	▲	●			●
Protozoa for example, <i>Cryptosporidium</i>	TT	▲	▲	●			●
Heavy metals for example, arsenic	10 µg l ⁻¹	▲			●	●	●
Inorganic anions for example, fluoride	4 mg l ⁻¹	▲				●	●
Pesticides for example, atrazine	3 µg l ⁻¹			●	●		●
Aromatics for example, benzene	5 µg l ⁻¹			●	●		●
DBPs for example, TTHMs	80 µg l ⁻¹				●		●
Precursors of DBPs for example, NOM		▲			●	●	●
PFOA	0.004 µg l ^{-1a}				●	●	●
PFOS	0.004 µg l ^{-1a}				●	●	●
Cationic and anionic precursors			▲	●	●	●	●
Non-ionic and zwitterionic precursors			▲	●	●		●

Triangles indicate conventional treatment techniques that can remove a specific group of contaminants from water when operated optimally. Circles indicate enhanced and advanced treatment techniques that can remove a specific group of contaminants from water when operated optimally. Clar., conventional clarification treatments consist of coagulation/flocculation (or lime-soda softening) and sedimentation; GMF, granular media or sand filtration; TT, treatment technique; TTHMs, total trihalomethanes. Precursors in this table refer to polyfluoroalkyl substances that can transform into PFOA and PFOS during water treatment. Currently, there are no federally established MCLs for NOM, cationic and anionic precursors, or non-ionic and zwitterionic precursors. ^aProposed federal MCL. Note that only a subset of heavy metal ions, inorganic anions, pesticides, aromatic compounds and DBPs are regulated under the SDWA, each with a specific MCL or treatment technique.

BOX 1

US EPA-recommended techniques for PFAS removal in water treatment

The US EPA considers GAC, IX and high-pressure membrane filtration to be the best available techniques for removing PFAS from natural waters based on several factors¹¹, including

- their high efficiency in removing PFAS,
- a track record of full-scale operation,
- applicability across a wide range of geographical locations,
- reasonable cost for use in large and metropolitan water systems, service life, compatibility with other water treatment processes and
- the ability to ensure compliance for all water in the system.

GAC and IX have been proposed as small-system compliance technologies affordable for public water systems serving populations of less than 3,300 (ref. 11).

PFAS found in diverse environmental and biological samples^{49,53–61}, suggesting their widespread occurrence in the environment. Precursors have been identified both in the drinking water serving communities close to contaminated areas and in the blood samples of individuals from these communities, indicating a possible route for human exposure to precursors via the consumption of tainted water⁶².

An often-overlooked aspect of PFAS management is the precursor compounds that can transform into perfluorinated compounds (for example, PFOA and PFOS). Compelling evidence indicates that some

instances of PFOA and PFOS contamination in drinking water may arise from the transformation of precursor compounds, or polyfluoroalkyl substances, in drinking-water disinfection processes^{16,63–66}. Therefore, regulatory bodies and water utilities should pay attention to these precursors as they can serve as ‘hidden sources’ that may eventually contribute to the burden of perfluorinated compounds (for example, PFOA and PFOS⁶⁵) in water supplies. Removing precursor compounds before disinfection would be necessary to prevent the de novo formation of perfluorinated compounds such as PFOA and PFOS.

Furthermore, many countries require a minimum disinfectant residual, measured as total chlorine, as an easily measured parameter to indicate water quality in distribution systems. Consequently, the generation of perfluorinated compounds from precursor compounds, if not removed from the water before the disinfectant/oxidant addition, may occur in storage facilities and distribution systems⁶⁷. Monitoring and control measures aimed at precursor compounds will enhance the overall effectiveness of PFAS management. While the US EPA analytical methods⁶⁸ are the benchmark for detecting PFAS in water samples, they encompass only a limited number of precursors. Recent advancements in analytical techniques such as high-resolution mass spectrometry^{48,50,69–71} and total oxidizable precursor assay^{72–75} are emerging as promising tools for identifying and quantifying precursors. However, there is a lack of standardized methods for precursors that can offer higher sensitivity and specificity, which would enable water utilities and regulatory agencies to expand the range of PFAS they monitor.

PFAS-containing spent media and waste streams

Treatment systems employing GAC and IX generate spent media containing PFAS, which necessitates proper handling and disposal. Limited options exist for addressing these solid wastes containing PFAS. The US EPA has taken several notable steps to manage these chemicals to protect public health and the environment from the potential hazards of waste disposal. In October 2021, the agency announced initiatives to

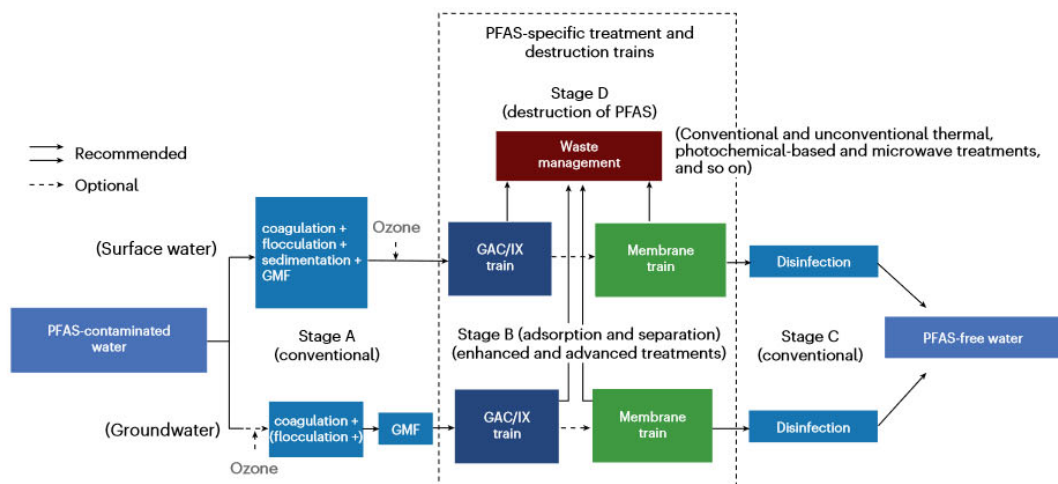


Fig. 2 | A multi-barrier treatment system potentially effective for PFAS removal from water in full-scale DWTPs. Schematic representation of a multi-barrier treatment system for PFAS removal in full-scale DWTPs. The process flow is divided into stages: Stages A and C (conventional) include coagulation, flocculation, sedimentation, GMF, and disinfection, as indicated by the blue boxes. The dark blue and green boxes in Stage B (adsorption and separation) represent enhanced and advanced treatments using the GAC, IX, or high-

pressure membrane filtration train, critical for removing SOC, including PFAS. The final Stage D (red box) involves waste management and destruction of PFAS, highlighting the importance of handling PFAS-containing wastes to prevent environmental release. The dashed lines denote optional treatments, such as additional ozone treatment, reflecting the system's adaptability based on the water source and contamination levels.

evaluate existing data on four PFAS (PFOA, PFOS, PFBS and HFPO-DA) under the Resource Conservation and Recovery Act to bolster the corrective action process for PFAS contamination⁷⁶. In August 2022, the agency formally proposed designating PFOA and PFOS as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)⁷⁷, commonly known as Superfund Law. This proposed rule-making is intended to improve transparency regarding PFAS releases and to hold responsible parties accountable for remediation. In April 2023, the US EPA issued an Advance Notice of Proposed Rulemaking⁷⁸, soliciting public input on the potential future designation of additional PFAS, including HFPO-DA, as hazardous substances under CERCLA. This Advance Notice of Proposed Rulemaking follows the agency's 2022 proposal to designate PFOA, PFOS, their salts and structural isomers as hazardous under the same act. Although the only official proposal so far involves designating PFOA and PFOS as hazardous substances under CERCLA, these initiatives could lead waste management facilities to decline acceptance of spent media containing PFAS. Consequently, DWTPs may be obligated to send PFAS-laden spent media to facilities specifically permitted for hazardous waste disposal, which could increase the financial burden on these DWTPs.

Furthermore, IX backwash/regeneration waste streams and nano-filtration (NF) or reverse osmosis (RO) brine demand treatment and disposal to avoid reintroducing PFAS into water sources or the natural environment. While various methods are available to degrade PFAS, practical and economic challenges may arise when implementing these methods for treating IX/NF/RO waste streams containing high levels of inorganic salts, colloidal particles and dissolved organic matter.

Technical and non-technical considerations

Notwithstanding the challenges noted above, practical strategies and approaches to remove PFAS in DWTPs are an urgent need for the water treatment community. Both technical and non-technical factors should be considered when selecting and implementing suitable treatment processes. This Perspective primarily addresses the technical aspects of PFAS removal and maintaining water quality. However, it is worth noting that various non-technical factors, such as socioeconomic status, cost

considerations, availability of financial resources, stakeholder engagement, public acceptance, community involvement, and legal and liability issues, affect the implementation of lasting solutions. Encouraging stakeholder engagement, public acceptance and communication fosters transparency, trust and community involvement in the decision-making process. An effective communication strategy is vital for addressing public concerns regarding PFAS and potential increases in monthly water bills resulting from the addition or upgrading of treatment units or processes. Economic and financial factors determine the affordability and feasibility of treatment options. Approximately 67% of community water systems in the United States serve populations of fewer than 500 people in rural communities⁷⁹. Although large water systems may have sufficient financial resources and technical expertise to address the PFAS issue, much assistance will be needed for numerous small systems in rural areas and Indian tribes to ensure equal access to safe drinking water.

Treatment options

Treatment trains for removal and destruction of PFAS

As presented in Table 1, physicochemical methods—namely, GAC adsorption, IX and high-pressure membrane filtration—are the commercially available and viable means for PFAS removal from water in full-scale applications^{16,80–86}. While these methods are effective individually for certain types of contaminant, a multi-barrier treatment system is often recommended to ensure the comprehensive removal of a broader range of pollutants, including PFAS. Utilizing multiple treatment steps in a coordinated fashion enhances the overall reliability and effectiveness of the treatment process, safeguarding against the limitations inherent in any single method.

In this study, we recommend a multi-barrier treatment train, referred to as the OAD method, representing an oxidation–adsorption–destruction-based method for effectively removing PFAS from contaminated water. This treatment train consists of (1) an optional oxidation process, using ozone or other conventional oxidants, designed to decompose a wide range of organic contaminants typically present in natural waters and to break down NOM into smaller molecules (Table 1), (2) adsorptive removal using GAC or IX, with NF/RO as an optional post-treatment step, and (3) destruction of PFAS in spent

media and waste streams (Fig. 2). The extent of implementing these processes will depend on a combination of the final MCLs and the magnitude and diversity of PFAS chemicals at a particular water source. Furthermore, DWTPs are designed and operated for multiple treatment objectives and compliance requirements. Thus, the final combination of process selection will require a holistic assessment of all these requirements.

Upgrading drinking-water treatment facilities

Figure 2 presents a conceptual design of an upgraded conventional water treatment system incorporating OAD. The proposed design is a four-stage surface water treatment system consisting of conventional clarification and separation processes (stage A), GAC/IX beds with or without post-separation treatments (stage B), a disinfection process (stage C) and a PFAS waste management process (stage D). While land-filling and underground injection technologies may be considered in the disposal of PFAS waste⁸⁷, treatment in this application is a process that includes managing spent media and waste streams in permitted facilities. For communities using groundwater as the drinking-water source, direct filtration (without sedimentation) (Fig. 2), in-line filtration (without flocculation and sedimentation) or lime-soda softening can be considered.

Critical components of OAD involve the separation of PFAS from water and the subsequent destruction of PFAS in spent media (for example, GAC) and waste streams (Fig. 2). GAC adsorption treatment was once proposed as a treatment technique for water utilities vulnerable to possible contamination by synthetic organic chemicals (SOCs) in late 1970s⁸⁸. This proposal was eventually abandoned, partly due to concerns over the economics related to the treatment. However, the price of GAC has dropped since then, and GAC contactors are easy to deploy in water treatment facilities. The ‘new’ challenges posed by PFAS could revive the idea of setting GAC adsorption treatment as an enforceable treatment technique and fundamentally upgrade DWTPs to tackle water contamination by SOC, including PFOA, PFOS and their precursor compounds (Table 1). An additional advantage of the GAC/IX adsorption process is the simultaneous removal of other organic contaminants (Table 1), thus further improving the final effluent water quality. Placing the adsorptive removal process, typically GAC, ahead of the disinfection stage allows for a reduction of NOM that otherwise contributes to the formation of DBPs during the subsequent disinfection step.

Sorption isotherms of PFOS, PFOA, GenX and PFBS on GAC can show pronounced nonlinearity with concave-downwards curvatures^{89–92}. This implies a considerable increase in adsorption (coefficient) as the PFAS concentration decreases during treatment. For this reason, GAC may be particularly effective for treating PFAS at low concentrations. Previous studies have suggested that bituminous coal-based GAC outperforms coconut-based GAC products in adsorbing PFAS from water^{83,93}. Furthermore, meso- and macroporous adsorbents (both activated carbon and resin) showed high adsorption capacity because long-chain PFAS may easily access mesopores, facilitating more effective adsorption⁹⁴.

PFAS removal from water can also be achieved with IX (Fig. 2). An IX vessel can be installed after the conventional treatment processes (stage A; Fig. 2) or downstream of GAC filters as an abatement measure. Certain types of IX resin effectively remove PFAS^{83,95} (Table 1). The conventional regeneration processes of spent resins consist of backwashing the system, injecting the regenerant compound, displacing the regenerant compound and finally rinsing the system. However, there is ample evidence that PFAS-laden IX resins are challenging to regenerate by conventional resin regeneration approaches^{96,97}. As a result, in the IX treatment process for PFAS removal, two types of waste are generated: (1) IX regenerant brine and (2) spent resins that are laden with PFAS. This differs from GAC adsorption processes, which primarily generate one type of waste (that is, spent carbon). Recent laboratory

studies show that electrochemical^{43,98} and plasma⁹⁹ treatments can effectively manage PFAS-laden IX brine, providing avenues for sustainable disposal. However, the spent resins pose a unique challenge. Given the absence of data on the long-term leachability of PFAS from used resins, landfilling these materials is not recommended. Current methods for managing PFAS-containing spent resins include thermal treatment¹⁰⁰ and high-temperature incineration¹⁰¹, as these are shown to degrade the PFAS compounds. However, it is imperative that these thermal disposal methods meet containment standards to minimize the release of harmful by-products from PFAS. The dual challenges posed by IX waste streams underscore the importance of developing comprehensive, effective and sustainable disposal methods.

Short-chain PFAS are much less bioaccumulative than long-chain homologues. The serum (or blood) elimination half-life of PFBS in humans is 26–44 days^{102,103}, compared with 3–5 years for PFOS^{102,104}. However, short-chain PFAS may be high enough in locations near point sources to raise health risk concerns. Both GAC and (regenerable) IX resins are ineffective for removing weakly hydrophobic, short-chain PFAS from water⁸³. Single-use resins with a high affinity for PFAS have been developed. In bench- and pilot-scale studies, non-regenerable resins are more effective than both GAC and regenerable IX for short-chain PFAS removal in water^{40,41}; however, further studies are needed to evaluate the cost-effectiveness of single-use resins. An upstream abatement train that includes GAC adsorption is recommended to lower the concentration of competing solutes, including long-chain PFAS.

Separation of short-chain PFAS from water can be achieved by high-pressure membrane processes. NF or RO membranes with low-molecular-weight cut-off are effective for removing a wide spectrum of contaminants, including short-chain PFAS, precursor compounds of PFOA and PFOS, and most of the regulated contaminants in water (Table 1). However, the influent to NF or RO usually needs to be pre-treated with microfiltration and ultrafiltration, which will add to the overall cost of treatment and bring financial burden to rural communities. In addition, inorganic fouling (for example, by calcium sulfate) may limit IX and NF/RO for treating (hard) water containing high levels of dissolved minerals, and organic and biological fouling can occur with NF/RO.

Treatment of PFAS-containing waste streams and spent media

Waste streams. Limited scalable options exist for treating PFAS-containing waste streams and spent media. The US EPA's interim guidance has outlined thermal destruction, landfilling and underground injection as available technologies for managing concentrated PFAS waste⁸⁷. However, the agency has not endorsed any method as a definitive solution. Laboratory-scale research has also explored several other treatment technologies for PFAS in IX regenerant, including plasma⁹⁹, electrochemical oxidation¹⁰⁵ and sulfate-radical-based advanced oxidation¹⁰⁶. Treatment of PFAS-containing IX/NF/RO waste streams by GAC adsorption, photocatalysis, advanced oxidation, reductive defluorination and sonolysis has been studied and reviewed elsewhere^{107,108}.

Spent media. Regenerating PFAS-laden GAC and IX resins is difficult using inorganic salts (for example, sodium chloride) or methanol only^{96,97,109}, as PFAS molecules are far more hydrophobic than inorganic anions such as Cl[–]. Thermal decomposition emerges as a promising approach for disposing of spent resins laden with PFAS, as supported by recent studies^{100,101}. One study illustrates that thermal treatment at low temperatures (for example, 200 °C) can effectively degrade short-chain perfluoroalkyl carboxylic acids and perfluoroalkyl ether carboxylic acids in spent resins¹⁰⁰. However, it is essential to emphasize that for the safe and efficient scaling of this technology, controlling the emission of by-products remains a critical consideration.

Thermal regeneration (≤ 300 °C) or reactivation (700–1,000 °C) of spent GAC is a common industry practice. While our understanding of the fate of PFAS in thermal processes has improved, there

is still much to be learned. Recent studies have shed light on this topic^{33,100,109–116}. It has been shown that reactivating spent GAC at $\geq 700^\circ\text{C}$ for 30 min can result in near-complete degradation ($>99.99\%$) of various types of PFAS¹⁰⁹, including PFOA, PFOS and short-chain PFAS (for example, PFBS) that are difficult to degrade by chemical and physical means. Polyfluoroalkyl substances are more susceptible to degradation than their perfluoroalkyl counterparts because their non-fluorinated moiety is more prone to thermal side-chain stripping¹¹⁷.

While thermal treatment appears promising for PFAS destruction, certain challenges remain. For instance, thermal treatment can result in carbon loss (5–10%) and produce gaseous by-products during the thermolysis of PFAS, as noted by Yao et al.¹¹⁸. However, several mitigation strategies exist. Research has indicated that elevating the treatment temperature can mitigate the formation of volatile organofluorine compounds¹¹⁸ and enhance the rate of PFAS mineralization^{109,113}. Moreover, existing literature has shown that plasma-based technologies can effectively degrade volatile organofluorine compounds^{119–121}. Substances such as kaolinite¹²² or lime¹²³ have proven to be effective in reducing the emission of reactive fluorine species, such as hydrofluoric acid.

The environmental community has also explored innovative regeneration methods of PFAS-laden GAC and IX resins⁹⁴, including the use of microwave irradiation¹²⁴; it is possible to defluorinate PFAS compounds over 90% at a relatively short regeneration time (3 min) with minimal impact on the GAC porous structure for several adsorption and regeneration cycles. In other studies, a concentrate-and-destroy technique has been developed that involves the adsorption of PFAS on a GAC-based adsorptive photocatalyst and subsequent destruction of sorbed PFAS by photolysis^{84,125}.

These technologies offer promise for treating PFAS-containing waste streams and spent media. However, further research is warranted to evaluate their scalability, economic viability and environmental impacts in pilot and full-scale operations. For example, microwave irradiation for GAC regeneration has shown potential in lab-scale tests, warranting further study in larger-scale applications. Another avenue should be to investigate how these technologies can be strategically integrated into existing treatment trains for maximum efficiency. A multi-barrier approach that combines, for instance, adsorption followed by photocatalysis could maximize PFAS removal and destruction^{84,125}. Pilot and full-scale trials of these technologies could pave the way for more comprehensive and effective strategies for PFAS treatment. This dual focus—on scalability and integrated treatment approaches—will be crucial for devising long-term solutions to the challenges posed by PFAS in waste streams and spent media.

In the near term, thermal destruction is a promising route for treating concentrated PFAS waste, given its capacity for high degradation efficiency^{87,126}. Our long-term goal should be to develop and implement destruction technologies that can comprehensively eliminate all PFAS, while minimizing adverse impacts on the environment and public health. Key considerations for evaluating any such technology include its applicability across a broad spectrum of PFAS compounds, as well as the specifics of its efficacy trials—such as the types of PFAS monitored and the media in which they are present (for example, spent filters, reject water and air emissions). In addition, the energy requirements and the nature and safety of any by-products generated must be scrutinized. Thorough data collection on these fronts is imperative for establishing confidence that a chosen technology meets the desired characteristics for effective and responsible PFAS management.

Removal of precursor compounds

Water utilities vulnerable to contamination by precursor compounds of perfluorinated compounds can optionally use an oxidation upstream of GAC adsorption as a treatment method. This process, as shown in Fig. 2, involves applying ozone after conventional treatments and using it either in conjunction with GAC adsorbents (post-ozonation)

or before conventional separation treatments (pre-ozonation). Ozonation has the added benefit of inactivating pathogens and oxidizing iron and manganese to form metallic oxide or hydroxide precipitates^{127,128} (Table 1). Moreover, ozonation breaks down NOM and many SOC to a more biodegradable form^{129–131} (Table 1), often followed by biologically active GAC filters to remove biodegradable compounds, including ozonation by-products^{88,132}. While PFOA and PFOS show resistance to ozonation, their precursor compounds are susceptible to degradation by ozone^{65,133}.

Applying ozonation before chlorine disinfection may allow the use of substantially less chlorine and better control of the formation of chlorinated DBPs. It is worth noting, however, that ozonation may lead to the formation of bromate, a DBP regulated under the SDWA, and promote biological growth in the distribution system when treating surface waters with high-organic-matter content.

Non-treatment considerations

Early detection and prevention

The forthcoming implementation of MCLs for PFOA and PFOS and the hazard index for PFNA, HFPO-DA, PFHxS and PFBS necessitate (1) statewide surveys of the concentrations of these compounds in drinking-water sources; and (2) appropriate management of drinking-water sources to prevent the contamination by PFAS. Both tasks involve geo-environmental factors and socioeconomic issues affecting the set objectives and solutions. For example, water sampling and analysis are often impeded by the high cost of analytical quantification of PFAS. To be effective, a prioritization framework or ranking system may be developed to strategically deploy resources by identifying and focusing on the suspect or known PFAS hotspot regions and/or point sources of PFAS contamination, including landfills, fire-training sites, airports, plating shops, refineries, and active or abandoned PFAS manufacturing sites. Monitoring raw water allows for the early identification of PFAS contamination sources, enabling proactive measures to prevent or mitigate their entry into the water supply, which could reduce the burden on treatment systems.

Development of localized databases of PFAS in raw, filtered and treated water, and consumer tap water

We recommend the development of localized databases to track PFAS levels in various stages of the water treatment process, including raw water, filtered water, treated water and consumer tap water. These databases will serve two purposes for local water treatment facilities: (1) to evaluate the treatment performance and seasonal variability and (2) to estimate the conditional probabilities of exceeding the corresponding federal/state MCLs and hazard index for PFAS. A multi-stakeholder approach is recommended to implement and maintain the proposed database. While public water systems stand as critical contributors due to their role in water treatment and routine monitoring, the involvement of state and federal regulatory agencies is essential for data validation and for ensuring alignment with regulatory benchmarks. Furthermore, contributions from academic institutions and non-profit organizations can provide valuable third-party research and monitoring insights. By focusing on localized data, these databases have the potential to offer detailed insights into the efficacy of PFAS removal during drinking-water treatment that is often site specific and subject to geological and seasonal variations. These data could eventually feed into broader state or national databases, creating a comprehensive resource for evaluating treatment performance, understanding seasonal variability and estimating the likelihood of exceeding the MCLs for regulated PFAS.

A suggested standard operating procedure to identify the causes of and respond to the continuous failure to meet the MCLs

Ideally, a standard operating procedure should identify both the generic cause, such as sampling, analysis and cross-contamination

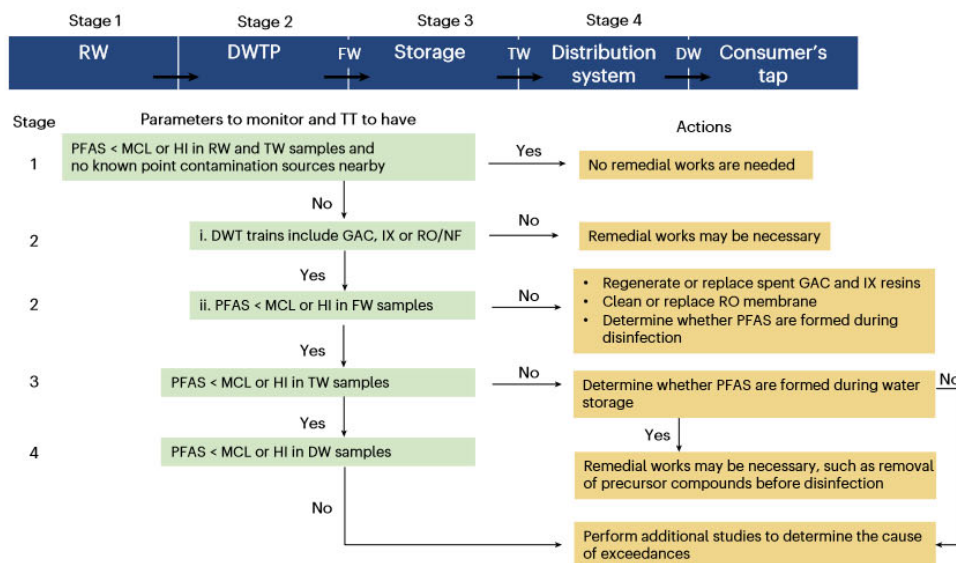


Fig. 3 | A phased approach to monitor PFAS in the public water system. This figure depicts a phased approach to monitoring PFAS in the public water system, indicating a sequence of stages from raw water through drinking water treatment to the consumer's tap. The process flow identifies critical monitoring points for PFAS, with corresponding actions ranging from no remedial action to potential

system upgrades or additional studies based on PFAS levels relative to the MCL or Health Index. Green boxes represent decision points, and orange boxes denote the required actions, ensuring safe drinking water compliance and public health protection. DW, drinking water; FT, filtered water; RW, raw water; TW, treated water; HI, hazard index; DWT; drinking water treatment.

issues, and the specific cause of the failure, including the breakthrough of PFAS in GAC or IX beds or NF/RO membranes with broken fibres.

A phased approach can be implemented to monitor PFAS concentrations in raw, finished and treated water (outlet of water reservoir or tank) (Fig. 3). Stage 1 involves determining PFAS removal efficiency by analysing raw and treated water sampling results. Monitoring frequency can be gradually phased in based on population size, similar to chlorinated and brominated DBPs. For example, large systems may require monitoring four times a year for DBPs, while the smallest system serving less than 500 people may only require annual monitoring¹³⁴. If the PFAS concentrations in treated water are consistently lower than the respective MCLs or hazard index, no remedial action is necessary. Stages 2 and 3 involve examining PFAS removal effectiveness and efficiency of the treatment systems (Fig. 3). The exceedance of PFAS concentrations over corresponding MCLs or hazard index in finished or treated water can indicate various issues, such as (1) the lack of a treatment technique that is known to remove PFAS from water (such as GAC adsorbers), (2) inappropriate management of the treatment trains (such as IX resin and RO membrane fouling), or (3) the generation of PFAS during disinfection treatment and water storage from precursor compounds. In such cases, remedial action may be required. Finally, the exceedance of PFOA and PFOS concentrations over corresponding MCLs in consumer tap water but not in treated water suggests the transformation of precursors in the distribution system.

Other non-treatment options

For small DWTs, non-treatment options can be considered, such as constructing new wells in an uncontaminated aquifer or interconnecting with and purchasing water from other public water systems¹¹. However, the feasibility of these non-treatment actions largely depends on the amount of water that needs to be replaced.

Summary

The past 20 years have seen a substantial increase in our understanding of the chemical, physical, thermal and biological stability of PFAS. This improved fundamental understanding is leading to remarkable

technological developments. However, the successes in removing and degrading PFAS in the laboratory have not occurred equally in the water industry. All available evidence suggests that the conventional drinking-water treatment systems (coagulation, flocculation, sedimentation, filtration and disinfection) are ineffective in removing PFAS from water. We argue that the solution to address critical challenges in effectively removing PFAS from natural waters in full-scale applications lies in the strategic integration and enhancement of commercially available treatment trains. Despite certain major drawbacks (regenerability, residual stream treatment and relatively high cost), adsorption and separation of PFAS from water by GAC, IX and NF/RO are the only commercially available technological solutions to treat PFAS-contaminated water in full-scale applications. It is also time for regulatory agencies to consider new, enforceable treatment techniques in addition to the conventional drinking-water technologies in DWTs to adequately address current and future challenges associated with SOC contamination of drinking water.

Furthermore, navigating the complex regulatory landscape of PFAS in drinking-water treatment presents considerable challenges for water utilities and communities alike. The presence of these persistent and harmful compounds in drinking-water sources requires urgent action and careful consideration of potential solutions. While there is no one-size-fits-all approach to addressing PFAS contamination, several possible paths can be tailored to the unique circumstances of each situation. These may include source control measures, enhanced treatment technologies, and effective communication and stakeholder engagement, as outlined in this paper.

Finally, following the recent passage of the Infrastructure Investment and Jobs Act in the United States, we anticipate substantial improvements in water infrastructure in the near future. These upgrades will be essential to ensuring compliance with state and federal regulations on PFAS and may also address other concurrent water-quality issues, including DBPs and toxic metals. Local water regulatory authorities have the opportunity to leverage federal funding to modernize outdated conventional drinking-water treatment systems. Ultimately, a collaborative and proactive approach that prioritizes

public health and environmental protection is essential to successfully navigating the maze of PFAS regulation and ensuring safe and reliable drinking water for all.

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Acknowledgements

This development of this paper was supported by US Environmental Protection Agency STAR Program (RD839660), US Department of Defense SERDP (ER22-4014; ER22-4015; ER18-1515), US Department of Defense ESTCP (ER21-5152), US National Science Foundation CAREER Program (2320966), US National Science Foundation (CBET 1805718; CBET 2041060) and Water Research Foundation (Project 5103). P.R. acknowledges partial support from European Union (NextGenerationEU), through the MUR-PNRR project SAMOTHRACE (ECS00000022). D.D. acknowledges support from the University of Cincinnati through the Herman Schneider Professorship in the College of Engineering and Applied Sciences. This paper is dedicated to the memory of Dionysios Dionysiou, who sadly passed away on 20 November 2023. The environmental community mourns the loss of a giant, a beloved scholar, and an amazing man. He will be deeply missed by us. We honour his legacy, which continues to impact the field and inspire future generations of researchers.

Author contributions

F.X. led the conception and the writing of the paper and the data analysis and plotting. All other authors, namely, B.D., D.D., T.K., K.O'S., P.R., Z.J.X. and D.Z., jointly contributed to the conception and writing of the paper. Each also provided valuable feedback on every section.

Competing interests

The authors declare no competing interests.

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Peer review information *Nature Water* thanks Giacomo DeFalco and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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