

PFAS contamination in drinking water systems near industrial zones: Bioaccumulation, human exposure risks, and treatment technology challenges

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Abstract

Per- and polyfluoroalkyl substances (PFAS) have emerged as persistent and hazardous contaminants in global drinking water systems, with industrial zones identified as significant point sources. These synthetic compounds, widely used in manufacturing processes for their heat resistance and non-stick properties, resist environmental degradation, leading to long-term accumulation in water, soil, and biota. Their persistence poses substantial risks to public health, particularly in communities located near industrial discharge sites where PFAS concentrations in surface and groundwater often exceed regulatory thresholds. Once ingested through drinking water, PFAS compounds bioaccumulate in human tissues, particularly the liver and blood serum, and have been associated with adverse outcomes such as thyroid disruption, immune dysfunction, and carcinogenic effects. This abstract explores PFAS behavior in drinking water systems near industrial areas, emphasizing the mechanisms of environmental persistence, migration into aquifers, and human exposure pathways. It also discusses the challenge of bioaccumulation through contaminated water and the amplification of risk via trophic transfer. From a treatment perspective, current technologies such as activated carbon adsorption, ion exchange resins, and high-pressure membrane filtration struggle with operational cost, selective removal efficiency, and secondary waste management. The complexity of PFAS chemical diversity further complicates removal strategies, particularly for short-chain variants. While regulatory efforts and monitoring frameworks are evolving globally, there is an urgent need for integrated approaches that couple advanced treatment innovations with real-time monitoring, community engagement, and remediation of contaminated sources. This issue is not only a technical challenge but a socio-environmental imperative, requiring collaboration among scientists, policymakers, and industry to mitigate long-term human and ecological risks.

Keywords: PFAS; Drinking Water; Bioaccumulation; Industrial Zones; Human Exposure; Water Treatment Technologies

1. Introduction

1.1. Contextual Overview of PFAS as Emerging Contaminants

Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic chemicals comprising over 12,000 compounds, characterized by their carbon-fluorine bonds among the strongest in organic chemistry [1]. These compounds have been extensively used in industrial and consumer applications, including firefighting foams, non-stick cookware, waterproof textiles, and electronics manufacturing. While PFAS have been beneficial in enhancing product durability, they are now globally recognized as emerging environmental contaminants due to their extreme persistence, bioaccumulative properties, and toxicity [2].

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PFAS are often referred to as “forever chemicals” because they resist degradation in natural environments and biological systems. Their presence has been detected in groundwater, surface water, soils, and even remote Arctic ecosystems [3]. Due to their ability to migrate long distances and their strong affinity for proteins, PFAS can enter the food chain and accumulate in blood, liver, and kidney tissues in both humans and wildlife.

Health studies have linked long-term PFAS exposure to a range of adverse effects including immunotoxicity, thyroid disruption, developmental delays, and increased cancer risks [4]. Unlike conventional pollutants, PFAS cannot be removed by standard wastewater treatments, requiring advanced technologies for remediation.

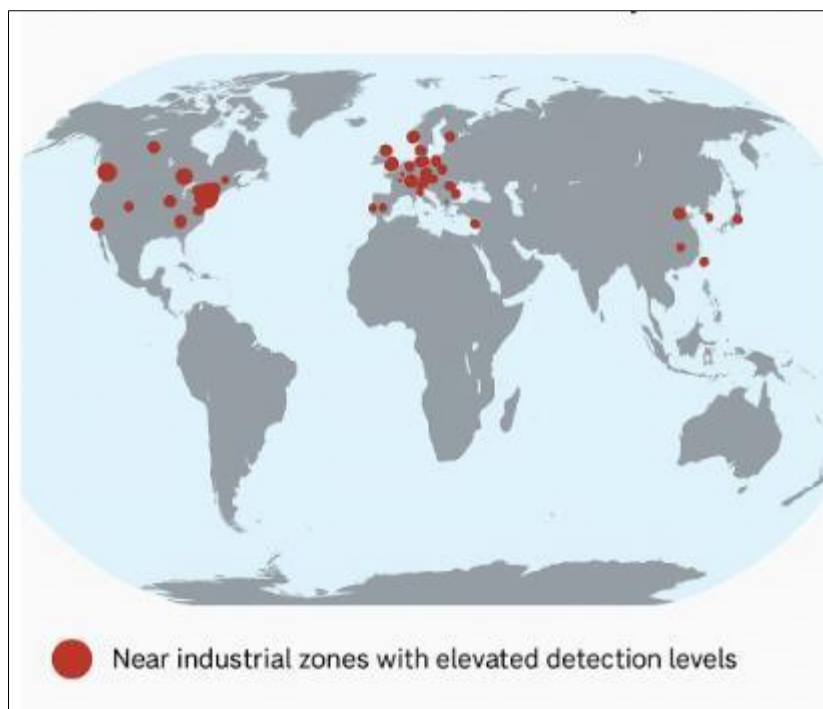


Figure 1 PFAS contamination hotspots globally, highlighting areas near industrial zones with elevated detection levels, particularly in North America, Europe, and East Asia [5]

1.2. Importance of Clean Drinking Water in Proximity to Industrial Zones

Access to clean and safe drinking water is a foundational human right and essential for public health. However, populations residing near industrial zones are increasingly at risk of exposure to PFAS due to improper disposal practices, leaching from landfills, or unregulated discharges into aquatic ecosystems [5]. Studies have shown that industrial activities such as electroplating, chemical manufacturing, and textile treatment are primary contributors to PFAS pollution in adjacent water sources [6].

Drinking water systems located downstream from industrial sites often face higher PFAS concentrations, especially when groundwater serves as the primary municipal source. Contaminated aquifers may persist for decades due to the chemical stability of PFAS compounds, and treatment plants designed for conventional pollutants are typically unable to remove them [7]. This raises concerns not only about chronic exposure but also about the equity and vulnerability of communities living near industrial corridors.

Recent reports from the United States Environmental Protection Agency (EPA) and European Environment Agency (EEA) confirm that PFAS levels in many public water systems exceed recommended health advisory limits, indicating systemic gaps in detection, monitoring, and remediation [8]. Therefore, examining PFAS distribution in industrial catchments is critical to developing responsive regulatory frameworks and infrastructure planning that protect drinking water integrity.

1.3. Rationale for Examining Bioaccumulation and Treatment Challenges

One of the most concerning aspects of PFAS exposure is their tendency to bioaccumulate in biological tissues, leading to long-term health risks even at low environmental concentrations. PFAS molecules mimic fatty acids and bind to

proteins in the liver and blood, allowing them to persist in the human body for years [9]. Once ingested through drinking water or food, they resist metabolism and are not readily excreted, resulting in cumulative toxicological effects over time.

Moreover, traditional water treatment methods such as coagulation, sedimentation, or chlorination are largely ineffective against PFAS. Advanced processes such as activated carbon adsorption, reverse osmosis, and ion exchange resins are required, often at considerable operational and financial cost [10]. Rural and underserved regions may lack the resources to implement such technologies, exacerbating environmental justice concerns.

Given the widespread detection of PFAS and limitations in treatment efficacy, it is imperative to study both their bioaccumulation dynamics and technical barriers to effective removal.

1.4. Scope and Objectives of the Article

This article examines the intersection of PFAS contamination, bioaccumulation, and treatment complexity in water systems located near industrial zones. Specifically, it investigates how PFAS compounds infiltrate drinking water supplies, how they bioaccumulate across aquatic and terrestrial ecosystems, and what technological and regulatory challenges hinder effective mitigation.

The analysis focuses on high-risk areas as visualized in Figure 1, offering a global perspective on exposure risks and vulnerability. Case studies will explore contamination in North America, Europe, and East Asia, contextualized with community health outcomes and remediation strategies.

Furthermore, the article evaluates current removal technologies, highlighting limitations in their scalability, cost, and operational feasibility. The objectives are to (1) synthesize existing research on PFAS behavior in water systems, (2) assess treatment effectiveness in industrial regions, and (3) propose integrated approaches for monitoring, risk assessment, and policy reform.

This study aims to support evidence-based responses to emerging PFAS threats in critical water infrastructure [11].

2. Pfas sources and environmental fate

2.1. Industrial Use and Emission Pathways

The industrial utility of per- and polyfluoroalkyl substances (PFAS) spans several decades, driven by their unique thermal stability, chemical inertness, and hydrophobic/oleophobic properties. These compounds are widely applied in manufacturing, firefighting, and surface treatment sectors, becoming integral to numerous industrial and consumer goods [6].

One of the primary industrial uses of PFAS is in the formulation of aqueous film-forming foams (AFFFs), which are employed for rapid fire suppression, particularly in military bases, airports, and petrochemical sites. These foams contain long-chain PFAS such as perfluorooctane sulfonate (PFOS), which persist in the environment after deployment [7]. In metal plating and electronic fabrication, PFAS are used as surfactants and mist suppressants due to their resistance to high temperatures and chemical degradation [8].

In the textile, leather, and packaging industries, PFAS impart stain-resistant and waterproofing features. This results in widespread pre-consumer and post-consumer PFAS discharge, especially in regions with large-scale textile processing facilities. Fluorinated polymers used in non-stick cookware and weather-resistant coatings further contribute to environmental loading through volatilization and degradation [9].

The release of PFAS into water systems primarily occurs through industrial effluent discharge, where wastewater from production lines carries PFAS residues into municipal treatment systems or directly into nearby water bodies. Since conventional wastewater treatment plants are not equipped to remove these persistent chemicals, PFAS often pass through untreated or partially treated [10].

Over time, continuous emissions from such facilities contribute to cumulative contamination in both surface and groundwater reservoirs. Industrial discharges, if unregulated or insufficiently monitored, remain one of the most concentrated sources of PFAS infiltration into surrounding aquatic ecosystems.

Table 1 Physicochemical Properties and Environmental Behavior of Selected PFAS Compounds

Compound	Carbon Chain Type	Water Solubility (mg/L)	Log BAF	Half-Life in Humans (years)	Environmental Persistence
PFOA	Long-chain (C8)	9.5	3.2	2.3	Very high
PFOS	Long-chain (C8)	680	3.8	5.4	Very high
PFNA	Long-chain (C9)	10.0	3.4	4.3	Very high
PFHxA	Short-chain (C6)	95.0	1.9	<0.5	Moderate
PFBS	Short-chain (C4)	730	1.6	1.0	Moderate
GenX	Short-chain (C6, ether)	200	1.7	<0.5	Unknown/under investigation

2.2. Transport Mechanisms to Water Systems

Once released into the environment, PFAS compounds migrate through several pathways, ultimately reaching surface water bodies, groundwater aquifers, and drinking water sources. These compounds are highly mobile, particularly the short-chain PFAS, which exhibit greater water solubility and lower sorption to soils compared to their long-chain counterparts [11].

A major transport mechanism is leaching from contaminated soils and landfills. Industrial waste containing PFAS whether solid sludge or residual liquids can infiltrate unsaturated zones during rainfall events. This process transports PFAS vertically through the vadose zone until it reaches the water table, contaminating aquifers used for human consumption [12].

Surface runoff is another significant vector, particularly during storms or firefighting events. When PFAS-laden water flows over impervious surfaces or contaminated ground, it accumulates in drainage systems and rivers. Runoff near airports or industrial zones where AFFFs have been applied can produce long-lasting contamination in downstream ecosystems [13].

Atmospheric deposition contributes to regional and even transboundary contamination. Volatile and semi-volatile PFAS compounds used in production such as fluorotelomer alcohols can be emitted into the air and transported over long distances. These airborne PFAS then deposit via wet or dry mechanisms, introducing contamination to remote lakes, glaciers, and forest ecosystems [14].

The migration of PFAS is also influenced by hydrological and geological conditions. In porous, sandy soils with low organic carbon content, PFAS can travel rapidly, complicating detection and containment. Once in the groundwater, these substances resist natural attenuation processes and can persist for decades, gradually moving with groundwater flow and expanding the contamination plume [15].

Notably, surface waters act both as recipients and redistribution media. PFAS entering rivers and lakes may undergo partitioning to sediments or be reintroduced into drinking water systems through abstraction. Understanding these transport vectors is critical to modeling exposure risk and guiding remediation efforts.

2.3. Environmental Persistence and Transformation

A defining characteristic of PFAS is their extreme environmental persistence, making them recalcitrant to degradation by natural processes such as biodegradation, photolysis, or hydrolysis. This persistence stems from the strong carbon-fluorine bond, which is among the most stable in organic chemistry and confers high resistance to thermal, chemical, and biological breakdown [16].

In both aerobic and anaerobic environments, PFAS demonstrate negligible microbial degradation. Studies show that standard microbial communities in wastewater treatment plants are unable to cleave the fluorinated chains, resulting in accumulation in biosolids and effluent [17]. Similarly, photolytic processes in surface waters fail to break down most PFAS compounds, particularly in turbid or shaded conditions.

However, transformation pathways do exist for precursor compounds, such as fluorotelomer alcohols (FTOHs) or perfluoroalkyl sulfonamido ethanols, which can degrade into terminal PFAS like PFOA or PFOS under specific environmental conditions. This precursor transformation complicates contaminant profiling and monitoring efforts, as detected PFAS may represent both primary pollutants and degradation byproducts [18].

Importantly, the environmental behavior and persistence of PFAS vary between short-chain and long-chain compounds. Short-chain PFAS such as perfluorobutanoic acid (PFBA) are more soluble and mobile, posing a higher risk of groundwater contamination, although they may exhibit lower bioaccumulation potential. In contrast, long-chain PFAS like PFOS and PFOA bind more readily to proteins and accumulate in organisms, making them a higher concern for food chain transfer and human exposure [19].

Table 1 presents a comparison of physicochemical properties such as water solubility, bioaccumulation factors, and half-lives of common PFAS compounds. It underscores the differential behavior of short- and long-chain PFAS in environmental media.

Understanding these dynamics is crucial for designing targeted remediation strategies and for assessing the long-term ecological and human health implications of PFAS-contaminated water systems [20].

3. Human exposure and bioaccumulation risk

3.1. Exposure Pathways from Drinking Water

Among various environmental exposure pathways, ingestion of contaminated drinking water remains the most significant route for human exposure to PFAS, especially in communities near industrial zones or affected aquifers [12]. PFAS are water-soluble, particularly the short-chain variants, and can persist in treated municipal supplies that lack advanced removal technologies. Once ingested, these chemicals bypass hepatic first-pass metabolism and enter systemic circulation, allowing them to interact directly with various organs.

The contribution of household plumbing systems to PFAS exposure, although less direct than industrial sources, can be non-negligible. PFAS-containing sealants, gaskets, or polymer-based linings used in water distribution systems may leach trace amounts of perfluoroalkyl acids over time [13]. Additionally, point-of-use water storage containers, particularly those made from fluorinated plastics, have been shown to leach PFAS compounds into stored water, further elevating chronic exposure levels [14].

In rural or unregulated water systems, where private wells are common, the lack of mandatory PFAS testing exacerbates the exposure risk. Wells near airports, waste disposal sites, or firefighting training centers frequently show PFAS levels exceeding health advisory limits set by regulatory agencies [15]. Since boiling water does not remove PFAS and may even concentrate it communities relying on such sources are disproportionately vulnerable.

Repeated ingestion over years leads to cumulative internal exposure, particularly as certain PFAS compounds exhibit long biological half-lives. This internal persistence is concerning because it sustains exposure even after external sources are mitigated. As depicted in Figure 2, ingested PFAS compounds accumulate in organs such as the liver, kidneys, and thyroid, with systemic effects that may manifest long after the initial exposure window has closed.

3.2. Mechanisms of Bioaccumulation

The unique bioaccumulative behavior of PFAS arises from their strong affinity for proteins rather than lipids, setting them apart from many other persistent organic pollutants. Upon ingestion, PFAS bind to serum albumin and other plasma proteins, facilitating their transport throughout the body and enabling tissue-specific accumulation [16].

Long-chain PFAS such as perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) show particularly high retention in the liver, kidneys, thyroid, and blood serum due to strong interactions with transport proteins and cellular membranes [17]. These compounds resist enzymatic breakdown and are poorly excreted via urine or feces, resulting in serum half-lives ranging from 3.5 to over 8 years depending on the compound and the individual's metabolic capacity [18].

Short-chain PFAS like perfluorobutanoic acid (PFBA) and perfluorohexanoic acid (PFHxA) tend to be more water-soluble and are excreted more rapidly. However, their mobility allows them to contaminate broader water systems, and

their frequent presence in commercial replacements for long-chain PFAS raises concerns about cumulative exposure from frequent contact, despite their lower bioaccumulation potential [19].

Bioaccumulation is not uniform across populations or age groups. Variations in physiology, renal function, and protein expression influence the distribution and retention of PFAS compounds. Infants and fetuses, for example, are exposed in utero and through breast milk, as PFAS easily cross the placenta and accumulate in maternal tissues [20].

Moreover, bioaccumulation varies among PFAS subclasses. Sulfonates generally demonstrate higher bioaccumulation than carboxylates due to stronger protein binding. For instance, PFOS has a notably higher volume of distribution and longer half-life than PFOA [21]. Figure 2 illustrates this differential bioaccumulation across organs, emphasizing the long-term retention in the liver and kidneys, while Table 2 outlines comparative metrics from human biomonitoring studies.

Understanding these mechanisms is critical for toxicokinetic modeling and for developing guidelines on PFAS exposure limits in drinking water, especially as bioaccumulative potential informs long-term risk assessments.

3.3. Health Impacts and Vulnerable Populations

Long-term PFAS exposure through drinking water has been linked to a range of adverse health outcomes, many of which are supported by both animal toxicology and human epidemiological studies. Given their persistence and bioaccumulation in critical organs, PFAS compounds can disrupt endocrine, immune, and metabolic systems, even at low environmental concentrations [22].

A well-documented association exists between PFAS exposure and thyroid dysfunction, particularly with compounds like PFOS and PFOA. These substances interfere with thyroxine (T4) and triiodothyronine (T3) signaling, potentially altering hormone homeostasis, especially in children and pregnant women [23]. Disruption of thyroid function in early life stages can impair neurological development, metabolism, and immune regulation.

PFAS exposure is also linked to certain cancers, most notably kidney and testicular cancer. Epidemiological studies conducted in contaminated communities in the U.S. have demonstrated increased incidence rates correlated with serum PFAS levels, prompting regulatory agencies to classify PFOA as a potential carcinogen [24]. These associations are supported by animal studies showing tumor development in rodents exposed to PFAS over extended periods [25].

Immunotoxicity is another major concern. PFAS have been shown to reduce antibody production following vaccination and impair T-cell responses, with children being particularly vulnerable [26]. A growing body of evidence indicates that PFAS exposure reduces the efficacy of childhood immunizations, which could have broad public health implications, especially during outbreaks of vaccine-preventable diseases.

In terms of metabolic syndrome, elevated PFAS levels have been associated with dyslipidemia, insulin resistance, and obesity in multiple cohort studies. These conditions raise long-term risks of cardiovascular disease and type 2 diabetes, particularly in already susceptible populations [27].

Vulnerable populations face disproportionate health risks. Infants and fetuses, as mentioned earlier, can acquire PFAS burden through placental transfer and breastfeeding, leading to early-life exposure during critical developmental windows. Pregnant women face elevated risks of hypertension and preeclampsia, which have been associated with serum PFAS concentrations [28].

Immunocompromised individuals, such as cancer patients or transplant recipients, may experience exacerbated effects due to PFAS-related suppression of immune responses. Additionally, low-income and rural populations often relying on private wells may lack access to regular PFAS monitoring and treatment technologies, intensifying their exposure and subsequent health risks [29].

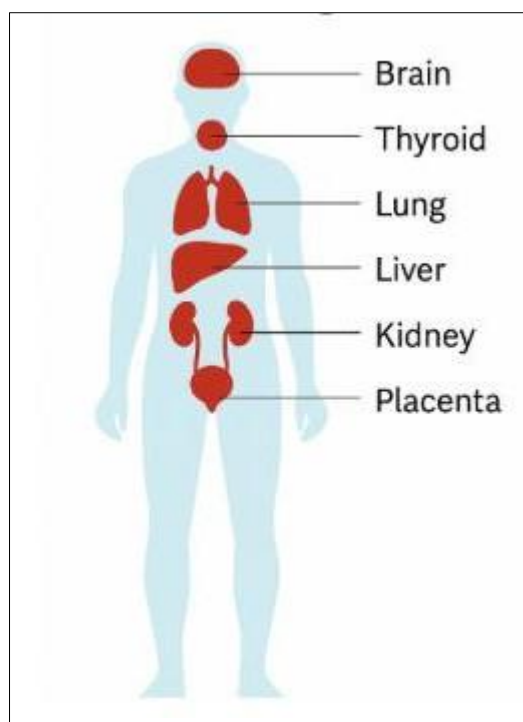


Figure 2 Offers a visual representation of PFAS accumulation in human organs following ingestion, illustrating organ-specific retention patterns. Table 2 summarizes key findings from epidemiological studies linking PFAS exposure to adverse health effects across various populations

Given the widespread detection of PFAS in drinking water supplies and the growing body of evidence on associated health impacts, urgent public health action is warranted to protect vulnerable groups and to guide risk-based water quality regulations [30].

4. Detection and monitoring strategies

4.1. Analytical Methods for PFAS Detection

Detecting PFAS in environmental and drinking water samples requires highly sensitive and selective analytical techniques due to their low concentration levels, complex chemical diversity, and persistence. The most widely adopted method is liquid chromatography-tandem mass spectrometry (LC-MS/MS), which allows for the accurate quantification of targeted PFAS compounds across various matrices [16]. LC-MS/MS combines chromatographic separation with mass-specific detection, making it suitable for routine monitoring of both short- and long-chain PFAS.

Time-of-flight mass spectrometry (TOF-MS) and high-resolution mass spectrometry (HRMS) further enhance detection by enabling the identification of non-target or unknown PFAS species based on molecular weight and fragmentation patterns. These techniques are essential for uncovering emerging PFAS not included in routine panels and for profiling complex mixtures in industrial discharges [17].

A crucial method for assessing total PFAS burden is the total oxidizable precursor (TOP) assay, which oxidizes precursor compounds into measurable terminal PFAS, such as perfluorocarboxylic acids. This assay provides a more complete picture of contamination levels, especially when precursor compounds dominate the pollution profile [18].

The method detection limit (MDL) for PFAS varies by compound and method but generally ranges from low parts per trillion (ppt) to sub-ppt levels. For instance, LC-MS/MS can achieve MDLs as low as 0.5 ppt for PFOA and PFOS in clean water matrices [19]. However, in complex matrices such as wastewater or landfill leachate, matrix interferences may elevate detection thresholds, requiring sample pretreatment like solid-phase extraction (SPE) or matrix-matched calibration.

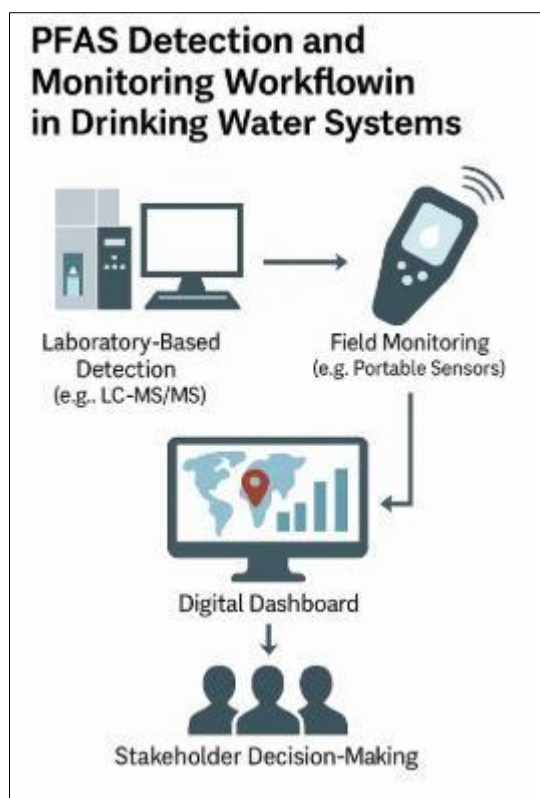


Figure 3 Real-Time Monitoring Flow for Inclusive Access Programs

Analytical accuracy and reproducibility are influenced by instrument calibration, internal standard recovery, and laboratory quality control protocols. Interlaboratory comparison studies have been critical in standardizing methods and ensuring data comparability across regions [20].

As part of regulatory frameworks, validated methods such as EPA Method 533 and EPA Method 537.1 are now widely used for PFAS detection in drinking water. These protocols emphasize both selectivity and sensitivity, forming the analytical backbone of surveillance systems deployed near industrial hotspots, as illustrated in Figure 3.

4.2. Spatiotemporal Monitoring Near Industrial Sites

Effective management of PFAS contamination near industrial zones necessitates spatiotemporal monitoring strategies that combine strategic sampling, geographic mapping, and long-term data collection. The goal is to assess not only the concentration of PFAS compounds but also their distribution patterns and changes over time [21].

Sampling design must consider location proximity to point sources, such as manufacturing plants, airports, or waste treatment facilities. Sampling points are typically established upstream and downstream of suspected discharge sites to understand PFAS dispersion through both surface and subsurface water pathways. In addition, vertical profiling in groundwater wells helps assess contamination depth and plume migration [22].

Temporal frequency is equally important. Seasonal variations such as rainfall, snowmelt, or industrial cycles can significantly affect PFAS concentrations in surface runoff and aquifers. As such, quarterly or monthly sampling is often recommended, with increased frequency during wet-weather events that accelerate PFAS mobilization [23].

Geographic information systems (GIS) are employed to map concentration gradients, identify hotspots, and visualize relationships between land use patterns and PFAS detections. These maps aid environmental health agencies in prioritizing remediation, notifying communities, and designing buffer zones [24].

Composite sampling and passive samplers are increasingly used in remote or resource-constrained regions to reduce sampling costs while maintaining temporal coverage. These devices absorb contaminants over extended periods, providing a time-integrated concentration profile rather than single-event measurements.

When coordinated with industrial reporting data and meteorological inputs, spatiotemporal monitoring enables predictive modeling of PFAS behavior in local hydrologic systems. As part of this framework, Figure 3 shows how field samples and automated sensors feed into centralized dashboards to visualize contamination levels in near real time.

4.3. Community-Based and Real-Time Sensing Innovations

As public awareness of PFAS risks grows, community-based monitoring programs have emerged as critical complements to institutional surveillance, especially in regions where regulatory oversight is limited. Citizen science initiatives empower residents to collect water samples, report contamination events, and engage with scientists through open data platforms [25]. These approaches foster transparency, democratize environmental science, and expand spatial coverage without extensive investment.

Portable PFAS detection devices are also gaining traction. While conventional LC-MS/MS remains the gold standard, new miniaturized sensors based on electrochemical, fluorescence, or immunoassay principles are being tested for field use. These sensors offer on-site detection capabilities, with turnaround times ranging from minutes to hours, making them suitable for rapid assessments and incident response [26].

Some technologies utilize molecularly imprinted polymers (MIPs) to achieve selective PFAS binding, improving accuracy in complex water matrices. Other innovations involve paper-based sensors capable of visual colorimetric changes when PFAS are present, although sensitivity remains a limitation [27].

Integration with digital dashboards enables real-time data visualization and risk communication. Cloud-connected sensors relay PFAS concentration data to centralized platforms, allowing stakeholders to monitor contamination patterns, issue alerts, and inform mitigation strategies. These platforms often incorporate AI-based analytics to detect anomalies and suggest sampling adjustments [28].

Community-collected data, when validated and standardized, can complement regulatory datasets, fill spatial data gaps, and inform local policymaking. Participatory approaches also build trust, particularly in historically marginalized communities disproportionately affected by environmental pollutants.

As illustrated in Figure 3, a modern PFAS monitoring workflow integrates both lab-based and real-time sensing technologies, with data flowing into collaborative interfaces that support multi-stakeholder engagement and dynamic decision-making at the municipal and regional levels.

5. Treatment technology landscape

5.1. Conventional Treatment Limitations

Conventional water treatment processes such as coagulation, sedimentation, and standard sand filtration are largely ineffective for removing PFAS from drinking water. These methods were designed to eliminate particulates, pathogens, and organic matter, but they do not address the unique chemical resilience and hydrophilic nature of per- and polyfluoroalkyl substances [20].

Coagulation, which involves adding chemical agents like alum or ferric chloride to aggregate contaminants into removable flocs, fails to target dissolved PFAS molecules. Studies have shown that even high concentrations of coagulants produce negligible reductions in PFAS concentrations, especially for short-chain compounds like PFBA and PFHxA [21]. Similarly, sedimentation, which relies on gravity to settle solids, cannot capture highly soluble PFAS species that remain in suspension.

Standard filtration typically involving sand or dual-media filters is also ineffective because PFAS molecules are too small and chemically inert to be adsorbed by traditional filter media. The low molecular weight and high water solubility of PFAS enable them to pass through filtration beds without significant interaction, leaving the finished water nearly as contaminated as the raw input [22].

These limitations are particularly critical in municipal plants that rely on legacy infrastructure. Even when combined with disinfection processes like chlorination or ozonation, conventional treatment offers no meaningful PFAS degradation, as these compounds resist oxidative and biological breakdown.

As illustrated in Figure 4, conventional treatment technologies fail to capture or destroy PFAS at any significant scale, necessitating the adoption of advanced treatment solutions. The continued reliance on traditional methods in PFAS-affected areas results in persistent exposure and delayed regulatory compliance, underscoring the urgency of infrastructure upgrades in high-risk zones.

5.2. Advanced Removal Technologies

To address the deficiencies of conventional treatment, utilities and researchers have turned to advanced treatment technologies capable of selectively removing PFAS from water. Among the most widely adopted are granular activated carbon (GAC), ion exchange resins, and membrane filtration methods, each with its strengths and operational limitations [23].

Granular Activated Carbon (GAC) is a porous material with a large surface area that adsorbs PFAS compounds through hydrophobic and electrostatic interactions. GAC is particularly effective at removing long-chain PFAS like PFOA and PFOS due to their stronger affinity for carbon surfaces. However, its efficiency declines for short-chain variants, which have weaker adsorption characteristics and require frequent media replacement [24]. GAC beds must be regularly regenerated or replaced, leading to increased operational costs and waste handling requirements.

Ion Exchange Resins are synthetic polymers functionalized to capture anions, including PFAS. These resins typically consist of quaternary ammonium functional groups that exchange chloride or hydroxide ions for negatively charged PFAS molecules. Ion exchange resins outperform GAC in removing short-chain PFAS, and they offer higher capacity and faster kinetics [25]. However, their selectivity varies with resin type, and some resins are prone to fouling in the presence of natural organic matter.

Reverse Osmosis (RO) and nanofiltration (NF) are membrane-based technologies that physically exclude PFAS molecules based on size and charge. These methods are among the most effective for broad-spectrum PFAS removal, including short- and long-chain compounds. RO membranes can achieve rejection rates above 95% under optimal conditions [26]. Nevertheless, membrane fouling, high energy consumption, and the generation of concentrated brine waste remain significant challenges.

The choice among these technologies depends on factors such as water matrix composition, target PFAS species, system capacity, and cost considerations. For instance, GAC is often preferred for large-scale municipal systems with long-chain PFAS contamination, while RO may be deployed in sensitive applications like hospital water systems or private well treatment.

Table 3 presents a comparative matrix of these advanced methods, evaluating their removal efficiency, cost per volume treated, operational complexity, and scalability. The table highlights that no single technology offers a universal solution, reinforcing the need for hybrid treatment trains combining GAC, ion exchange, and RO to optimize performance.

Table 2 Industrial Adoption of Non-Fluorinated Alternatives to PFAS Compounds

Sector	PFAS Use Case	Alternative Implemented	Performance	Environmental Persistence	Economic Viability
Textile Manufacturing	Water-repellent coatings	Silicon-based and wax emulsions	Moderate–High	Low	Moderate
Food Packaging	Grease barriers	Algae-based and plant-derived coatings	Moderate	Biodegradable	Moderate–High
Firefighting Foam (AFFF)	Flame suppression	Fluorine-free foams (e.g., Novacool)	Moderate	Low	Moderate–Low
Electronics	Etching and surfactants	Supercritical CO ₂ and ionic liquids	High (in lab)	Variable	Low (scaling challenges)
Cosmetics	Smooth finish and durability	Plant oils and polymers	Moderate	Low	High

Metal Plating	Surface tension modifier	Non-fluorinated surfactants	Moderate	Low	Moderate
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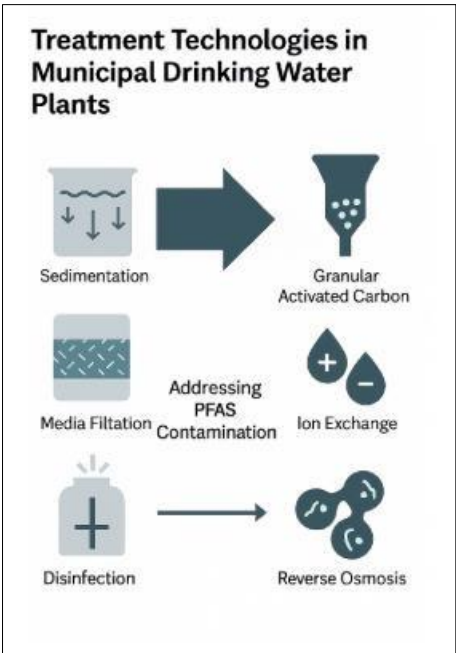


Figure 4 Further illustrates how these advanced technologies are integrated into upgraded municipal plants, replacing or supplementing traditional treatment stages to ensure regulatory compliance and protect public health

5.3. Novel and Emerging Approaches

Beyond established technologies, several novel treatment approaches are under investigation for PFAS removal and destruction. These methods aim not only to extract PFAS from water but also to mineralize or decompose the fluorinated compounds, reducing long-term environmental burden [27].

Electrochemical oxidation (EO) applies a direct electric current to contaminated water through specialized electrodes, generating reactive species like hydroxyl radicals. These radicals attack PFAS molecules, breaking carbon-fluorine bonds and converting them into harmless byproducts such as carbon dioxide and fluoride ions. Boron-doped diamond electrodes have shown promising results, particularly for degrading PFOA and PFOS, though their cost and scalability remain limiting factors [28].

Plasma treatment, specifically using non-thermal or corona plasma, creates a highly reactive environment where energized electrons initiate PFAS degradation. In gas-phase plasma reactors, PFAS-laden water is atomized, allowing plasma discharge to interact with aerosolized droplets. This method is effective at treating high-strength waste streams such as concentrated RO brine or AFFF residuals [29]. However, challenges related to energy intensity and byproduct formation persist.

Photocatalysis involves using light-activated materials such as titanium dioxide (TiO₂) or modified carbon-based catalysts to initiate PFAS degradation under UV or solar irradiation. Photocatalytic systems have demonstrated partial defluorination of short-chain PFAS, but complete mineralization remains difficult, especially in real-world matrices containing organic matter and competing ions [30].

Hybrid systems integrating EO and photocatalysis or plasma with pre-treatment adsorption are being explored to overcome limitations in single-stage processes. These emerging solutions promise lower environmental impact, smaller treatment footprints, and potential application for in situ remediation of PFAS-contaminated sites.

Though still in developmental stages, such innovations represent the next frontier in PFAS treatment, with pilot projects underway in the U.S., Europe, and East Asia. As regulations tighten and contamination hotspots expand, continued investment in research and commercialization of these technologies is critical for long-term sustainability.

5.4. Treatment Residue Management

A critical yet often overlooked aspect of PFAS mitigation is the management of treatment residues. Advanced technologies like GAC, ion exchange, and membrane filtration do not destroy PFAS they simply concentrate them in spent media, backwash water, or brine waste. Improper disposal of these byproducts risks reintroducing PFAS into the environment, negating treatment efforts [31].

Spent GAC and ion exchange resins are typically incinerated under high-temperature conditions ($\geq 1,100^{\circ}\text{C}$) to achieve thermal degradation of fluorinated compounds. However, concerns over incomplete combustion and the generation of toxic byproducts such as HF and PFHxS require careful emissions control and monitoring [32]. Alternatively, some waste streams are sent to hazardous landfills, though this option only delays future leaching risks.

Concentrated brine from RO and plasma treatment systems poses a separate challenge. Disposal via deep well injection is practiced in some regions but raises questions about groundwater migration and long-term geochemical stability [33].

Innovative strategies such as supercritical water oxidation (SCWO) and thermal desorption are being investigated for complete PFAS destruction in treatment residues. These approaches promise permanent remediation but are still constrained by scale and cost [35].

Table 3 includes data on the waste management implications of each treatment method, while Figure 4 visualizes how residue streams are handled within municipal treatment infrastructures, reinforcing the need for a closed-loop and sustainable remediation system [34].

6. Regulatory frameworks and policy gaps

6.1. National and International Guidelines

Regulatory bodies at the national and international levels have begun to establish health-based guidelines for PFAS in drinking water, though variations remain across jurisdictions. In the United States, the Environmental Protection Agency (EPA) released updated health advisories in 2021, recommending non-enforceable limits of 0.004 parts per trillion (ppt) for PFOA and 0.02 ppt for PFOS, reflecting their recognized toxicity and persistence [24]. These levels are far below previous thresholds and have prompted states to revise their standards to align with or exceed federal recommendations.

In the European Union, the EU Drinking Water Directive was revised in 2020 to include a group-based limit of 100 ppt for total PFAS and 500 ppt for 20 summed PFAS compounds, signaling a regional commitment to harmonized regulation [25]. Member states retain the authority to implement stricter limits, and several such as Denmark and the Netherlands have already adopted more stringent controls.

Globally, the World Health Organization (WHO) has proposed a guideline value of 100 ppt for PFOA and PFOS combined, noting the challenges of maintaining uniform standards across diverse water quality contexts [26]. While WHO guidelines serve as references, they are not legally binding and must be contextualized within national risk frameworks.

Despite progress, differences in targeted compounds, analytical methods, and enforcement mechanisms persist. The lack of unified global standards complicates cross-border trade, especially in food products and textiles containing PFAS residues. Table 2 compares threshold levels and target compounds defined by leading agencies, highlighting gaps and overlaps in current PFAS regulation.

As the understanding of PFAS toxicity evolves, dynamic updating of guidance levels is crucial to reflect toxicological findings, emerging compound classes, and advances in analytical detection, particularly in regions near industrial PFAS hotspots visualized in Figure 1.

6.2. Policy Enforcement Challenges

While regulatory frameworks for PFAS have gained momentum, implementation and enforcement remain fraught with systemic and logistical challenges. One key difficulty lies in compliance monitoring, especially for small and rural utilities that lack advanced laboratory infrastructure to detect PFAS at ppt levels [27]. Routine compliance testing using

LC-MS/MS or total oxidizable precursor (TOP) assays can be prohibitively expensive, limiting enforcement to well-resourced municipalities.

The financial burden of treatment upgrades also hinders compliance. Retrofitting water systems with granular activated carbon (GAC), ion exchange resins, or reverse osmosis systems entails substantial upfront capital and ongoing maintenance costs. These costs often fall on local governments and ratepayers, exacerbating socioeconomic disparities in access to clean water [28].

Further complicating enforcement is jurisdictional fragmentation. In federal systems such as the United States, authority over drinking water regulation is shared between state and federal agencies, leading to inconsistencies in enforcement. Some states, like Michigan and New Jersey, have implemented aggressive PFAS limits independently, while others rely on EPA advisories, creating a patchwork of standards [29].

There is also a lack of regulatory clarity surrounding emerging PFAS compounds. With thousands of structurally diverse PFAS in circulation, most regulations target only a narrow subset. This gap allows unregulated PFAS, including novel fluorinated alternatives, to escape monitoring and accumulate in ecosystems.

Enforcement efforts are further constrained by limited toxicological data. Regulatory thresholds must balance human health protection with feasibility, yet data gaps on many PFAS limit evidence-based standard setting. These challenges underscore the importance of dynamic, adaptive regulation and stronger collaboration between scientific institutions, water authorities, and industry stakeholders.

As indicated in Table 2, regulatory divergence and analytical capability gaps continue to challenge global PFAS governance, even as contamination expands across national boundaries.

6.3. Community Advocacy and Legal Actions

In the absence of consistent regulatory enforcement, community advocacy and legal action have emerged as powerful tools to demand accountability, transparency, and clean water access. Across contaminated regions, affected populations have mobilized through water justice movements, class-action lawsuits, and citizen science to elevate PFAS-related issues into the public and legal domain [30].

One prominent case is the litigation involving residents of Parkersburg, West Virginia, who sued DuPont in the early 2000s for PFAS contamination of local water supplies from a nearby manufacturing plant. The resulting settlement included compensation, medical monitoring, and the establishment of a scientific panel that confirmed links between PFOA exposure and health outcomes such as cancer and thyroid disease [31].

In Michigan, local communities around Wolverine World Wide tannery sites organized resistance and litigation after elevated PFAS levels were found in residential wells. The advocacy led to one of the largest PFAS-related settlements in the state's history and spurred regulatory reform in testing and disclosure requirements [32].

More recently, municipalities and school districts in North Carolina have filed lawsuits against PFAS manufacturers for polluting the Cape Fear River, a drinking water source for over 200,000 residents. These efforts have been supported by grassroots coalitions, environmental NGOs, and academic institutions conducting independent water monitoring.

Citizen science has played a vital role in mobilizing data and public pressure. Programs such as PFAS Exchange and Silent Spring Institute have equipped residents with sampling kits, education materials, and digital tools to map contamination and inform policymakers [33].

As Figure 3 demonstrates, integrating community-collected data into centralized dashboards not only enhances detection but also supports environmental justice by validating lived experiences. These movements exemplify how legal and civic action can complement policy reform and enforce corporate accountability where regulations lag behind.

7. Case studies and lessons from impacted regions

7.1. Case Study: Parkersburg, West Virginia

The city of Parkersburg, West Virginia, represents one of the most pivotal and well-documented cases of PFAS contamination in the United States. The contamination stemmed from decades-long discharge of perfluorooctanoic acid

(PFOA) a long-chain PFAS compound used in Teflon production by a nearby DuPont manufacturing facility [28]. The site began operations in the 1950s, and by the 1980s, internal documents revealed DuPont's awareness of PFOA's environmental persistence and potential health effects.

Residents of Parkersburg were exposed to contaminated drinking water over several decades, with elevated PFOA concentrations found in both municipal supplies and private wells. Community health concerns gained national attention in the early 2000s, prompting a class-action lawsuit against DuPont. As part of the legal settlement, the company funded the C8 Health Project, which gathered health data from over 69,000 affected individuals [29].

The epidemiological studies conducted by an independent science panel found probable links between PFOA exposure and a variety of health outcomes, including kidney cancer, testicular cancer, thyroid disease, ulcerative colitis, high cholesterol, and pregnancy-induced hypertension [30]. These findings laid the groundwork for stronger regulatory scrutiny and contributed to the global push to phase out PFOA from consumer products.

In response to the contamination, DuPont installed granular activated carbon (GAC) filtration systems in local water treatment plants and agreed to long-term medical monitoring for residents. The Parkersburg case not only underscored the severe public health risks associated with PFAS but also demonstrated the power of community-led litigation and scientific transparency in driving regulatory change.

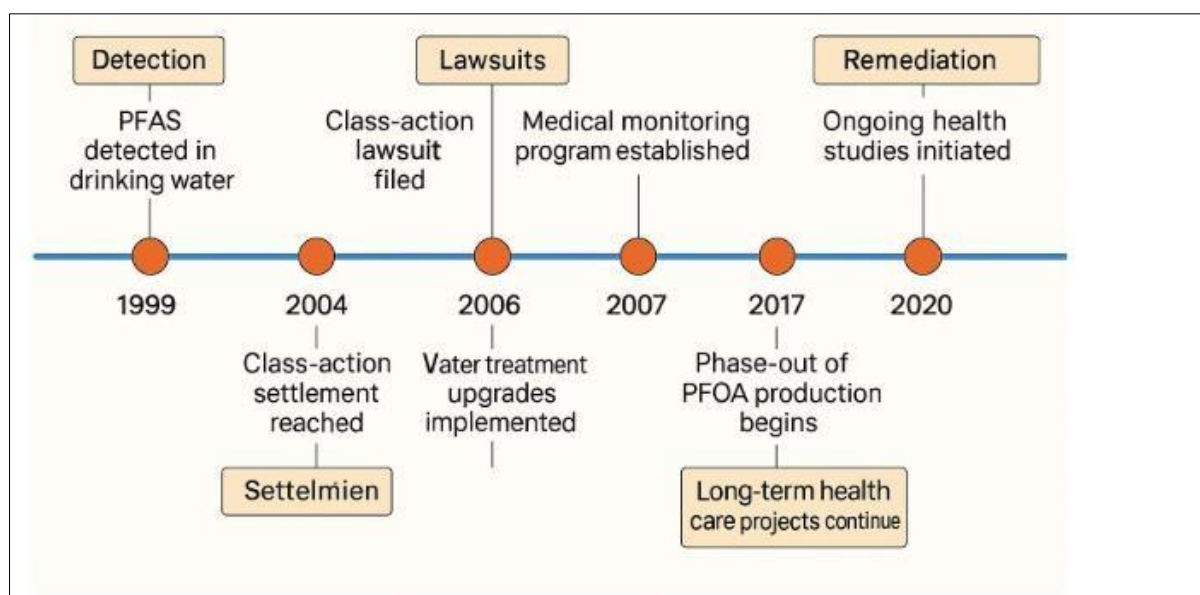


Figure 5 Visualizes key milestones in Parkersburg's PFAS timeline, from early detection and lawsuits to remediation and ongoing health interventions

7.2. Case Study: Netherlands Industrial Corridor

The Netherlands Industrial Corridor, particularly in the regions of Dordrecht and Rotterdam, has emerged as a critical European case study in managing transboundary PFAS contamination. Decades of industrial activity, including the use of GenX (hexafluoropropylene oxide dimer acid) as a substitute for legacy PFAS, led to widespread contamination of surface waters and agricultural soils [31].

In Dordrecht, a chemical facility operated by Chemours discharged GenX into the Merwede River, a water source for nearby communities. Despite regulatory frameworks under the European Union Water Framework Directive, national enforcement proved insufficient in the early years of GenX use. Elevated levels of PFAS were detected in drinking water supplies and rainwater catchment systems, prompting widespread public concern [32].

Recognizing the regional scale of contamination, the Dutch government initiated a multi-stakeholder remediation program that included cross-border cooperation with Belgium and Germany. Measures included stricter emission limits, extended PFAS monitoring zones, and the provision of clean water alternatives to impacted populations. The program also introduced soil reuse restrictions for contaminated construction materials to prevent secondary exposure pathways.

Legal and policy responses in the Netherlands emphasized the “precautionary principle”, leading to the adoption of lower PFAS thresholds than EU minimum standards. Public engagement played a pivotal role, with local municipalities publishing open-access PFAS data and collaborating with NGOs to develop citizen advisory boards [33].

This case illustrates the importance of harmonized environmental governance in addressing PFAS threats that transcend national boundaries and require collaborative, science-informed interventions.

7.3. Lessons Learned and Transferable Insights

The Parkersburg and Netherlands case studies offer critical insights for communities and policymakers managing PFAS contamination. One of the most salient lessons is the necessity of early intervention. In both cases, delayed regulatory responses led to prolonged public exposure, reinforcing the need for proactive monitoring, especially in industrial zones and vulnerable aquifers [34].

Transparent data sharing emerged as another essential component of effective response. The C8 Health Project in West Virginia and the open-access municipal databases in the Netherlands helped establish public trust and informed risk communication. Access to verified contamination data allows communities to participate meaningfully in remediation planning and public health responses [35].

Community engagement proved vital in initiating legal action, shaping policy, and ensuring accountability. In both case studies, resident advocacy drove the momentum for scientific investigation and legal restitution. These actions underscore the value of citizen science, local coalitions, and cross-sector partnerships in amplifying environmental justice claims [36].

A shared challenge across both contexts was addressing substitution chemicals, such as GenX, whose toxicological profiles remain incomplete. This highlights the importance of regulating PFAS as a chemical class rather than on a compound-by-compound basis.

Finally, both case studies emphasize the need for integrated remediation strategies combining source control, point-of-use filtration, and land-use planning. As shown in Figure 5, coordinated timelines linking detection, response, and mitigation create structured frameworks for managing PFAS crises and building community resilience.

These transferable lessons can inform global approaches to PFAS regulation, risk assessment, and sustainable remediation in both high-income and resource-limited settings.

8. Toward sustainable solutions: research and innovation roadmap

8.1. Green Chemistry Alternatives and Source Reduction

Addressing PFAS contamination sustainably requires prioritizing green chemistry principles and source reduction strategies at the production level. Rather than retrofitting solutions onto polluted systems, proactive substitution of hazardous PFAS compounds with safer alternatives can limit environmental release and long-term exposure [32].

In manufacturing, industries are gradually shifting away from long-chain PFAS, such as PFOA and PFOS, toward short-chain or fluorine-free alternatives. However, the safety profiles of replacement chemicals like GenX and ADONA remain under scrutiny, with emerging evidence suggesting similar bioaccumulative and toxicological concerns [33]. This calls for a precautionary approach and emphasizes the need for comprehensive life-cycle toxicity assessments before adoption.

Green chemistry research has explored non-fluorinated surfactants, silicon-based coatings, and biodegradable polymers as viable PFAS substitutes in textiles, firefighting foams, and food packaging. These materials demonstrate comparable performance under laboratory conditions but face challenges in terms of cost scalability, durability, and industry uptake [34].

Policy incentives and regulatory mandates can accelerate the market transition. For instance, procurement policies that favor PFAS-free products in government contracts have spurred innovation in Europe and North America. Similarly, extended producer responsibility (EPR) frameworks shift the burden of pollution control to manufacturers, encouraging upstream interventions.

As illustrated in Table 2, several industrial sectors have begun trialing or transitioning to non-fluorinated alternatives, with varied success in terms of performance, environmental persistence, and economic viability. Nonetheless, a system-wide transition to green chemistry will require coordinated investment, cross-sectoral collaboration, and international harmonization of substitution standards.

Table 3 Comparative Matrix of Advanced PFAS Treatment Technologies

Treatment Method	Removal Efficiency (%)	Cost per 1,000 Gallons (USD)	Operational Complexity	Scalability
Granular Activated Carbon (GAC)	70–95	0.25–0.50	Low	High
Ion Exchange Resin	85–99	0.50–1.00	Moderate	Moderate–High
Reverse Osmosis (RO)	>99	1.00–3.00	High	Moderate
Advanced Oxidation Processes	40–70	1.50–2.50	High	Low–Moderate
Electrochemical Treatment	60–90	2.00–4.00	Very High	Low
Thermal Destruction	~100	>4.00	Very High	Very Low (site-limited)

Upstream substitution remains one of the most effective strategies to prevent PFAS proliferation in ecosystems and drinking water, ultimately reducing the need for costly downstream remediation efforts and public health interventions [35].

8.2. Data-Driven Risk Forecasting and AI Applications

Technological advancements in predictive analytics and artificial intelligence (AI) offer promising tools to anticipate PFAS contamination and optimize mitigation strategies. By analyzing historical data on industrial activity, land use, hydrogeology, and regulatory reporting, AI models can identify future high-risk zones before contamination becomes severe [36].

Machine learning algorithms can integrate remote sensing data, climate models, and geospatial indicators to forecast PFAS plume migration and simulate the effectiveness of various remediation scenarios. This enables water authorities and environmental planners to prioritize sampling locations, allocate resources efficiently, and implement real-time surveillance systems [37].

In recent pilot projects, AI tools have been deployed to automatically detect anomalies in groundwater PFAS levels and trigger alerts when thresholds are surpassed. These systems have reduced monitoring costs and increased detection accuracy in regions lacking laboratory infrastructure.

Figure 3 Which illustrates the flow of real-time monitoring data, exemplifies how AI-enhanced dashboards consolidate sensor inputs, community reports, and policy thresholds into actionable insights

Despite these innovations, data scarcity and inconsistent reporting remain challenges. Continued investment in open-access PFAS datasets and interoperable analytics platforms will be essential to scale AI applications and ensure equitable environmental protection across jurisdictions [38].

8.3. Interdisciplinary Collaborations and Policy-Science Integration

Solving the complex PFAS crisis requires interdisciplinary collaboration that bridges environmental science, public health, data analytics, and regulatory policy. No single sector holds all the expertise or resources needed to address the chemical, ecological, and social dimensions of PFAS pollution [39].

Integrating health impact assessments, exposure science, and regulatory toxicology enables evidence-based policymaking that reflects real-world exposures and community vulnerabilities. For example, linking PFAS epidemiological data from Table 2 with land use models and drinking water monitoring can inform zoning regulations and resource allocation in high-risk areas.

Universities, regulatory agencies, and non-governmental organizations have begun forming PFAS research consortia that share data, standardize testing protocols, and develop harmonized response strategies. These consortia enhance transparency and public engagement, reinforcing trust in institutional responses to contamination crises.

International bodies, including the OECD and WHO, advocate for collaborative approaches that align research priorities with regulatory frameworks. This convergence is particularly vital for controlling PFAS use in global supply chains and ensuring compliance with evolving guideline values described in Section 6.1 and Figure 1.

To build resilient systems, policymakers must invest in platforms that support cross-disciplinary knowledge exchange, integrate community feedback, and translate scientific insights into enforceable standards and actionable policy [40].

9. Conclusion and future directions

9.1. Recap of Core Findings: Exposure Risks, Treatment Challenges, Policy Gaps

This article has highlighted the pressing public health and environmental threat posed by PFAS contamination in drinking water systems, particularly near industrial zones. Exposure through ingestion remains the dominant pathway, with cumulative accumulation in human tissues linked to multiple adverse health outcomes, including cancer, thyroid dysfunction, immunosuppression, and developmental toxicity. Despite the growing recognition of these risks, current treatment technologies such as activated carbon, ion exchange resins, and reverse osmosis remain financially and technically inaccessible for many communities, especially those in rural or under-resourced regions. Meanwhile, policy responses are fragmented across jurisdictions, with regulatory limits, target compound lists, and enforcement mechanisms varying widely between countries and even within national borders. These gaps hinder coordinated action and exacerbate disparities in clean water access.

9.2. Urgency of Integrated Mitigation Strategies

Given the complexity of PFAS behavior in environmental systems and their persistence across generations, an integrated mitigation approach is urgently needed. Such strategies should combine source reduction through green chemistry, real-time and community-based monitoring for early detection, equitable access to advanced treatment, and consistent regulatory frameworks informed by evolving science. Early intervention and transparent data sharing must be prioritized to prevent further harm and restore trust in affected communities. Coordination across sectors industry, academia, government, and civil society is essential for long-term success.

9.3. Research and Regulatory Outlook for Sustainable Drinking Water Protection

The path forward requires sustained investment in PFAS-free alternatives, predictive analytics for risk mapping, and global harmonization of safety standards. Strengthening interdisciplinary research, closing data gaps, and aligning environmental and health policies will be key to ensuring safe, sustainable drinking water systems for all populations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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