Comparative Lifecycle and Economic Analyses of Emerging PFAS Remediation Technologies for Groundwater and Surface Water in the United States

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Abstract:
Per- and polyfluoroalkyl substances (PFAS), often termed "forever chemicals," pose a growing threat to environmental and human health due to their persistence, resistance to degradation, and widespread contamination in groundwater and surface water. These pollutants are linked to serious health risks, including cancer and endocrine system disruption. Hence their remediation has become a critical priority for water management worldwide. This systematic review aims to synthesize and evaluate emerging PFAS remediation technologies from a comparative perspective, focusing on lifecycle environmental impacts and economic feasibility. Using the PRISMA guidelines, this study identifies and critically analyzes peer-reviewed literature published between 2020 and 2025. The advanced remediation methods reviewed include granular activated carbon (GAC), ion exchange resins (IX), electrochemical oxidation, and polymer-stabilized activated carbon. Key findings highlight significant trade-offs among these technologies: while some approaches like GAC and IX are cost-effective for large-scale deployment, they generate substantial secondary waste. In contrast, emerging methods like electrochemical and plasma-based treatments reduce secondary waste but face scalability challenges due to high energy consumption. Lifecycle assessments reveal that energy demands and material sustainability remain critical bottlenecks. The insights derived from this analysis emphasize the urgent need for integrated remediation strategies that balance effectiveness, cost, and environmental sustainability to meet regulatory standards. Policymakers, technologists, and stakeholders must align efforts to address research gaps, particularly regarding long-term technological feasibility, secondary pollution risks, and region-specific strategies. This review underscores the necessity of interdisciplinary collaboration to foster innovation and mitigate the pervasive threat of PFAS contamination.

Keywords: PFAS remediation, lifecycle analysis, economic analysis, emerging technologies, groundwater management.

1.0 INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are an expansive group of synthetic organofluorine compounds characterized by their robust carbon-fluorine (C-F) bonds, which confer environmental persistence and resistance to conventional chemical and biological degradation. For over half a century, these "forever chemicals" have been widely used in industrial and consumer applications, including firefighting foams, nonstick cookware, water-repellent fabrics, and food packaging (Wanninayake, 2021; Boyer et al, 2021; Asantewaa Adjei-Sah and Oduro, 2025). However, the same chemical stability that has made PFAS commercially valuable has also rendered them highly persistent in environmental matrices, particularly in groundwater and surface water systems. This attribute, coupled with their toxicological implications, has transformed PFAS contamination into a critical environmental and public health concern, both in the United States and globally (Yaghoobian et al, 2025).

PFAS are renowned for their recalcitrance against natural degradation processes, leading to their long-term presence in water systems and biologically active ecosystems. These compounds are detectable in diverse environmental media, including groundwater, surface water, soil, and even atmospheric deposition (Dobrzyńska et al, 2025). Their widespread distribution is attributed to point and non-point sources, such as industrial discharges, landfill leachate, and wastewater treatment plant effluents (Tang, 2023; Modiri, 2024). For instance, facilities handling aqueous film-forming foams (AFFFs) utilized in firefighting contribute significantly to the localized contamination of groundwater, as evidenced by studies documenting PFAS plumes migrating into drinking water reservoirs (Chambial P., et al 2025; McFarlan & Lemke, 2024).

The health risks associated with PFAS exposure are profound and diverse, encompassing endocrine disruption, reproductive toxicity, immunotoxicity, and increased risks for certain cancers. Bioaccumulation of specific PFAS compounds, such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) has been documented in food chains, particularly in aquatic systems (De Silva et al, 2021; Chambial et al, 2025; Fang et al, 2025). Drinking water contamination is a primary pathway for human exposure, making the remediation of PFAS in water resources a critical priority (Wee & Aris, 2023).

Furthermore, emerging PFAS variants and their precursors present new challenges, as their environmental fate and toxicity are less understood. This dynamic underscore the need for continuous monitoring, advanced characterization, and novel mitigation strategies to intercept these chemicals at the source and contain their dissemination.

The United States is grappling with the growing urgency of addressing PFAS contamination. Regulatory frameworks, such as the establishment of maximum contaminant levels (MCLs) by the U.S. Environmental Protection Agency (EPA), aim to reduce PFAS concentrations in drinking water to well below dangerous thresholds. Implementing these regulations requires scalable and cost-effective remediation technologies capable of meeting part-per-trillion (ng/L) standards (Chambial et al, 2025; Jafarinejad el at, 2025).

Traditional treatment methods, such as adsorption using granular activated carbon (GAC) or anion exchange resins (AER), remain the most widely deployed technologies. However, these approaches face significant limitations, including generation of secondary waste streams, high operational costs and diminishing selectivity for shorter-chain PFAS over time (Ellis et al, 2023; Asgar et al, 2025). Therefore, innovative solutions offering both environmental sustainability and economic feasibility are imperative.

Comparative analyses of lifecycle environmental impacts and the costs associated with emerging PFAS remediation technologies are crucial for informing decision-making processes (Yeih et al., 2025; Yeih & Kaiser, 2025). The integration of advanced techniques, such as electrochemical oxidation, plasma-based destruction, and membrane filtration, alongside conventional methods, can provide a richer understanding of performance trade-offs. Lifecycle assessment (LCA) and techno-economic analysis (TEA) methodologies offer valuable insights into these trade-offs, ensuring that the technologies adopted not only achieve regulatory compliance but also align with broader environmental and economic sustainability goals.

Recent years have witnessed significant advancements in PFAS treatment technologies. Among these, adsorption remains at the core of operational methodologies. GAC and AER systems are highly effective in removing a broad spectrum of PFAS compounds from contaminated water. However, single-use adsorbents eventually reach saturation, requiring disposal or regeneration processes that may introduce additional environmental burdens (Ellis et al, 2023; Murray et al, 2023).

Emerging technologies are attempting to resolve these limitations. For instance, electrochemical oxidation offers promising potential to destroy PFAS molecules by targeting C-F bonds via direct electron transfer mechanisms. This approach circumvents the issue of secondary waste generation but is hindered by high energy demands and scaling challenges (Hatton et al, 2025; Fang et al, 2025). Similarly, developments in advanced oxidation processes (AOPs), such as UV-assisted persulfate oxidation, target PFAS degradation through radical generation. The use of chemical precursors and overall process efficiency remains a concern.

Membrane-based separation techniques, including reverse osmosis (RO) and nanofiltration (NF), exhibit exceptional selectivity for PFAS removal but are energy-intensive and produce concentrated brine waste. Novel hybrid approaches, such as combining ultrafiltration membranes with photocatalytic reactors, promise lower energy consumption and enhanced PFAS removal kinetics, though current applications are limited to experimental scales (Junker et al, 2024).

Biological methods, such as bioadsorption and enzymatic degradation, are rising research themes. While not yet commercially viable at a large scale, these approaches align with green chemistry principles and may play a complementary role in integrated treatment strategies in ecologically sensitive areas (Ezeorba et al, 2024).
Despite these advancements, several critical challenges persist in addressing PFAS contamination effectively. Lifecycle assessments reported in the literature often neglect upstream and downstream environmental impacts, including the energy and material requirements of high-tech solutions. Additionally, there is a glaring lack of studies evaluating cross-media contamination risks, where treatment in one medium (e.g., water) results in pollutant transfer to another medium (e.g., air or soil) (Altmeyer Mendes et al, 2025; Asgari et al, 2025).

Current economic analyses are frequently constrained to operational costs, with inadequate attention to externalities, such as public health burdens or long-term environmental costs associated with PFAS persistence. Integrated LCA-TEA frameworks, capable of correlating environmental trade-offs directly with economic feasibility, are urgently needed (Murray et al, 2023).

Furthermore, scalability remains a significant barrier. Laboratory-scale innovations often experience diminished efficiency or disproportionate cost increases when applied to large-scale municipal or industrial water systems. Pilot-scale studies are rare, limiting the generalizability of most emerging technologies (Hatton et al, 2025; Liljeström et al, 2025). In particular, addressing region-specific challenges, such as PFAS variants that dominate certain industrial settings or water chemistries, is essential for effective remediation solutions.
This systematic review aims to synthesize and critically evaluate the recent advancements in PFAS remediation technologies, focusing on studies published between 2020 and 2025. By leveraging lifecycle assessments (LCA) and techno-economic analyses (TEA), the review seeks to provide a robust comparative framework highlighting effectiveness, scalability, and sustainability of various approaches.

2.0 METHODOLOGY

2.1 Database Selection

To ensure comprehensive coverage of relevant literature, searches were conducted in the following databases: PubMed, Scopus, Web of Science and Google Scholar

Boolean Search Strings

Specific Boolean operators were employed to maximize search specificity and sensitivity, such as: "PFAS treatment" OR "perfluoroalkyl substances" OR "polyfluoroalkyl substances" AND ("remediation technologies" OR "water treatment" OR "lifecycle analysis" OR "economic costs".
The search was constrained to English-language peer-reviewed articles published from 2020 to 2025, reflecting the most recent advancements and regulatory shifts. Review articles and primary research were both included, provided they included original experimental results or key aggregated insights.

2.2 Inclusion and Exclusion Criteria

A rigorous selection process defined the scope of acceptable papers:

Inclusion Criteria

- Peer-reviewed publications addressing PFAS-contaminated groundwater or surface water.
- Studies employing experimental, pilot-scale, or full-scale systems for remediation technologies.
- Articles containing lifecycle assessments (LCA), techno-economic analyses (TEA), or sustainability metrics.
- Research focusing specifically on U.S.-based implementations or global technologies adaptable to the U.S. regulatory framework.

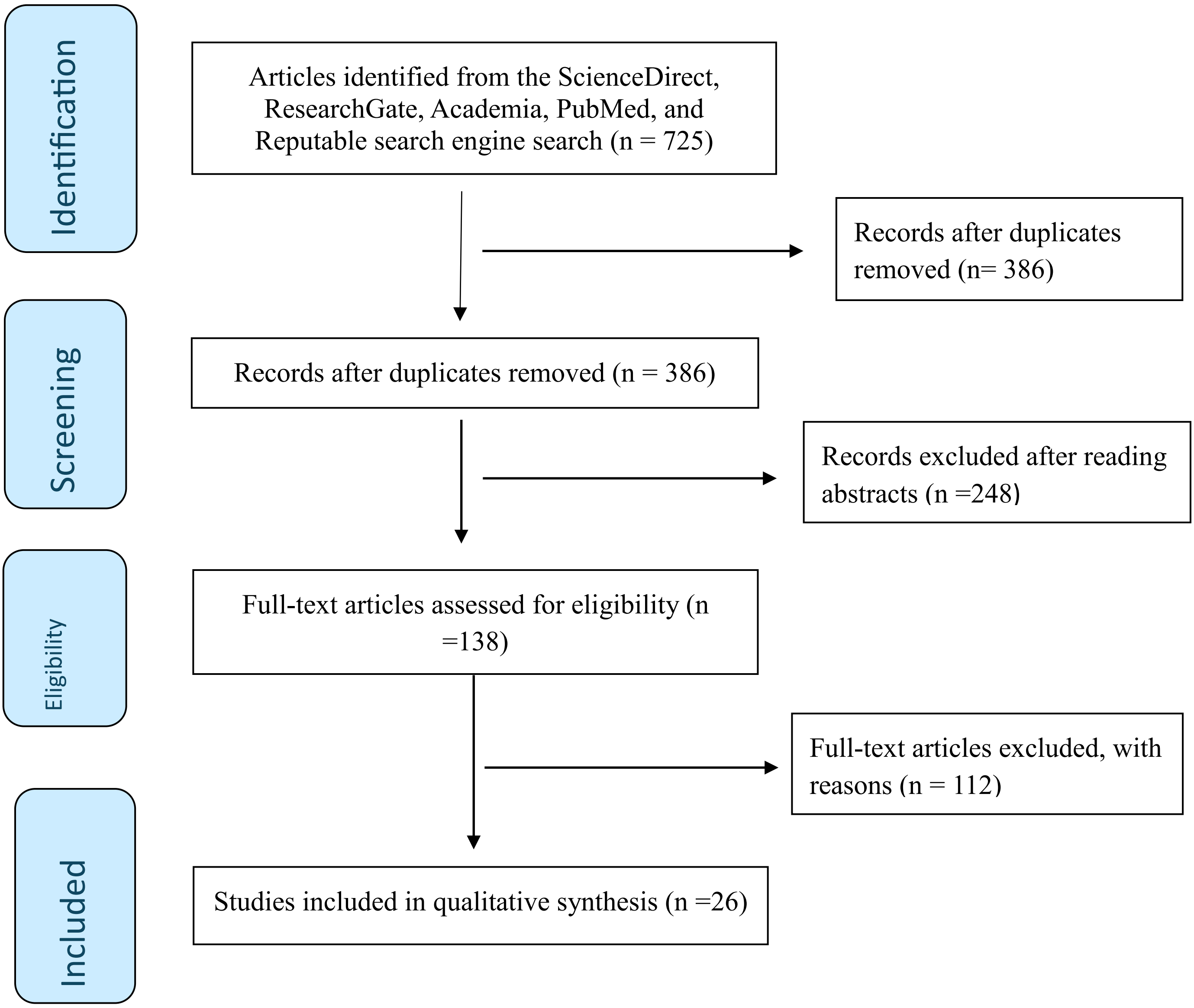
Exclusion Criteria

- Studies without sufficient experimental or analytical detail (e.g., commentary pieces).
- Articles primarily focused on PFAS effects in human health or wildlife without remediation focus.
- Papers analyzing non-scientifically validated technologies or without data on practical application (e.g., early-stage, theoretical approaches).

2.3 Screening Process

A stepwise PRISMA workflow was employed as follows:

Figure 1: PRISMA Flow diagram showing the article selection process in the study.



Sources; Author's Construct 2020.

3.0 RESULTS AND DISCUSSION

3.1 Overview of Emerging Technologies

Emerging PFAS treatment technologies exhibit innovative approaches toward mitigating contamination in groundwater and surface water. The table below shows different methods which represent state-of-the-art advancements in PFAS remediation:

Treatment Technology	Operating Principle	Efficiency	Limitations & Challenges
Electrochemical Treatment	Direct or indirect oxidation targeting C-F bonds. Direct methods use electrodes; indirect methods generate reactive species (e.g., hydroxyl radicals).	Up to 95% removal for long-chain PFAS in pilot studies. Shorter-chain PFAS degradation is often incomplete (Altmeyer et al, 2025; Hatton et al, 2025).	High energy demand, electrode fouling, need for advanced materials. Risk of forming toxic, partially degraded intermediates (Asgari et al, 2025). Scalability is hindered.
Plasma Technologies	Generates a reactive environment (electrons, ions, radicals) to break down PFAS molecules in water.	>90% degradation reported for PFOA/PFOS at lab scale, with minimal secondary waste (Chambial et al, 2025; Ezeorba et al, 2024).	High energy consumption per unit volume, complex system design, and costly reactor maintenance limit scalability (Asgari, 2025; Ezeorba et al, 2024).
Bioadsorption & Biodegradation	Bioadsorption uses biopolymers to adsorb PFAS. Biodegradation uses microbes/enzymes to metabolize PFAS.	Promising for low concentrations but immature. Efficiencies often <50% for many variants, including short-chain PFAS (Ezeorba et al, 2024).	Lack of biological mechanisms to break strong C-F bonds. Real-world contaminant levels often exceed microbial tolerance, reducing efficiency (Chambial et al, 2025; Arun et al, 2026).
Photocatalytic Treatment	Uses light-activated catalysts (e.g., TiO_2) to generate reactive species for degradation/mineralization. Explored in hybrid ultrafiltration membrane reactors.	Potential shown in integrated systems. Specific field efficiencies under investigation, aims for destructive removal (Lu et al, 2023).	Catalyst activation efficiency, risk of incomplete degradation/intermediates, scalability issues, and significant energy for UV light (Junker et al, 2024).
Treatment Technology	**Operating Principle**	**Efficiency**	**Limitations & Challenges**
Adsorption (GAC, Ion Exchange)	GAC: Physical adsorption onto porous surface. IXR/AER: Electrostatic binding to charged sites. Innovations include PFAS-selective resins and polymer-stabilized carbon (Ellis et al, 2023; Hatton et al, 2025).	High removal (85-99%) for a wide range, especially long-chain PFAS. Selective resins offer enhanced removal.	Generates PFAS-laden spent media requiring costly disposal/regeneration (Lu et al, 2023). Performance declines with competing organics or short-chain PFAS. Sustainable regeneration is critical.

Membrane Filtration (RO, NF, UF)	RO/NF: Size exclusion and charge repulsion. UF: Larger pores; used in hybrid systems (e.g., photocatalytic reactors).	RO/NF: >99% removal for most PFAS. UF: Shows promise in hybrid systems (Junker et al, 2024).	Energy-intensive (high pressure). Produces concentrated brine requiring further treatment/disposal. Sustainability concerns due to energy and waste management (Altmeyer et al, 2025).

Table 1. Comparative Analysis of Advancements Techniques in PFAS Remediation

3.2 Lifecycle Analyses

Lifecycle assessment (LCA) provides a comprehensive framework to evaluate the environmental footprint of PFAS treatment technologies from raw material extraction to disposal. This approach helps in understanding the broader ecological consequences beyond simple removal efficiency.

Energy Use and Carbon Emissions

Electrochemical methods and plasma-based systems typically exhibit higher energy footprints due to their reliance on specialized equipment and high-voltage electrical inputs. Energy demands for these advanced oxidative processes can range from 1.2 to 3.5 kWh per cubic meter of treated water, significantly exceeding those of adsorption-based systems, which generally require less operational energy. Comparative LCAs indicate that while destructive technologies like plasma and advanced oxidation minimize secondary waste, they often result in higher greenhouse gas (GHG) emissions during operation due to their energy-intensive nature (Altmeyer et al, 2025).

Waste Production

Granular activated carbon (GAC) and ion exchange (IX) systems generate substantial quantities of PFAS-saturated spent adsorbent waste. If these spent media are improperly managed, such as through incineration or landfill disposal without adequate safeguards, PFAS can be released back into the environment, thus perpetuating the contamination cycle (Ellis et al, 2023; Altmeyer et al, 2025).
In contrast, advanced destructive technologies, such as electrochemical oxidation and plasma treatment, aim for near-complete mineralization of PFAS, thereby reducing the volume and toxicity of waste streams. However, the complete reliance on these methods for municipal-scale applications is often impractical due to infrastructural limitations and high costs (Lu et al, 2020).

Geographical and Environmental Variability

Field studies consistently demonstrate that variations in groundwater chemistry, including the presence of co-contaminants, pH levels, and ionic strength, can substantially influence the performance and environmental impact of PFAS treatment technologies. For instance, membrane-based systems may experience reduced efficiency in brackish water due to increased fouling rates and salt accumulation, which necessitate more frequent cleaning and result in higher energy consumption (Junker et al, 2024). Similarly, the presence of natural organic matter can compete with PFAS for adsorption sites in GAC and IX systems, reducing their overall effectiveness and operational lifespan (Murray et al, 2023).

Economic Feasibility

The economic viability of PFAS treatment technologies is a critical factor determining their large-scale adoption and sustainability. Cost assessments encompass capital expenditures (CAPEX), operational expenditures (OPEX), and maintenance costs.

Cost Assessments

Capital expenditures for emerging methods vary substantially. While established technologies like GAC and IX remain relatively affordable, newer approaches such as electrochemical and plasma treatment typically involve significantly higher initial costs due to specialized infrastructure, advanced materials, and complex system designs. For instance, the operational expenditures for plasma technologies can exceed 45 per cubic meter of treated water, which is substantially higher than the approximately 45 per cubic meter of treated water associated with GAC treatment (Ellis et al, 2023).

Trade Offs

Advanced treatment methods, particularly destructive technologies, generally exhibit lower waste management costs because they aim for complete PFAS degradation, minimizing the need for disposal of PFAS-laden waste (Lu et al, 2020). However, their high energy demand and complex maintenance requirements often lead to longer payback periods and higher overall lifecycle costs. These economic factors frequently limit their widespread adoption to high-priority contamination sites or specific industrial applications, rather than broad municipal use (Ellis et al, 2023). Lifecycle cost-benefit analyses increasingly emphasize the potential benefits of integrated treatment frameworks. These frameworks combine lower-cost adsorptive technologies with advanced oxidative destructive methods to balance affordability with high removal and destruction effectiveness.

Controversies and Challenges

Despite significant advancements, several unresolved issues continue to hinder effective PFAS management and remediation efforts.

Secondary Waste Generation

Adsorption-based technologies, while effective for PFAS removal, invariably generate large quantities of PFAS-saturated materials that require careful and costly disposal. If these materials are not managed efficiently and securely, there is a substantial risk of reintroducing PFAS into the environment through leachate from landfills or emissions from incineration thereby undermining the initial treatment objectives and perpetuating contamination challenges (Ellis et al, 2023; Altmeyer et al, 2025).

Scalability of Laboratory Scale Technologies

Many innovative PFAS remediation technologies, such as enzymatic degradation and advanced plasma reactors, have demonstrated promising results at laboratory or bench scales (Lu et al, 2020; Ezeorba et al, 2024). However, a persistent challenge is scaling these technologies up to meet the demands of municipal water systems or large industrial sites. Often, performance diminishes, costs escalate, and operational complexities increase significantly when these technologies are deployed at a larger scale, hindering their practical applicability.

Long Term Efficacy

A critical gap in current research is the lack of extensive, long-term studies on the stability and functionality of treated environments or the long-term efficacy of deployed remediation technologies. Uncertainties persist regarding the behavior and potential transformation of PFAS degradation byproducts over extended periods. This limits scientific consensus on the true long-term benefits and environmental safety of various treatment techniques, making it difficult to guarantee sustained remediation and prevent unforeseen ecological impacts (Lu et al, 2020; Altmeyer et al, 2025).

Regional and Regulatory Impacts in the U.S.

The U.S. regulatory landscape, driven by federal and state-level initiatives, profoundly influences the adoption and prioritization of PFAS remediation technologies.

Federal Guidelines

The U.S. Environmental Protection Agency (EPA) has been instrumental in setting strict PFAS maximum contaminant levels (MCLs) for drinking water. These stringent guidelines, often requiring removal to part-per-trillion levels, drive significant interest in high-efficiency technologies capable of meeting such demanding thresholds. However, implementing these federal standards places immense financial strain on municipalities, particularly smaller and under-resourced communities, which may struggle with the capital and operational investments required for advanced treatment facilities (Lendewig et al, 2025).

State Level Innovations

Several U.S. states, such as California and Michigan, have adopted aggressive PFAS regulatory frameworks that often go beyond federal guidelines. These state-level initiatives create strong incentives for investments in advanced treatment facilities and the development of innovative remediation technologies. For example, some states have implemented broad PFAS testing requirements and stricter discharge limits, pushing industries and municipalities to seek more effective and permanent solutions for PFAS removal and destruction (Lendewig et al, 2025).

4.0 FUTURE DIRECTIONS AND RESEARCH GAPS

The exploration of future directions in PFAS remediation technologies and lifecycle analyses must focus on addressing persisting knowledge gaps, improving remediation strategies, and ensuring that practical, equitable, and sustainable solutions reach implementation. Here, we identify critical challenges revealed by recent research and propose actionable avenues for future studies to advance the field.

4.1 Knowledge Gaps Identified:

4.1.1 Long-Term Efficacy of Emerging Technologies

While laboratory and pilot-scale studies demonstrate promising results for techniques such as electrochemical oxidation, plasma treatment, and advanced membranes, long-term field-scale data are lacking. Questions remain about the durability of these systems, degradation byproducts, and potential decreases in efficiency.

Scalability Challenges: Technologies that demonstrate efficacy in controlled environments often face diminished performance and economic feasibility when scaled to municipal or industrial levels. This challenge is particularly evident in high-energy or maintenance-intensive methods.

Secondary Contamination Risks: Many processes produce byproducts, such as concentrated brine waste in desalination techniques or volatile intermediates in oxidation methods. The environmental fate, toxicity, and potential reintroduction of these byproducts into ecosystems remain poorly characterized.

PFAS Chemistry and Variant-Specific Barriers: Studies suggest that short-chain PFAS variants and precursor molecules are more challenging to remediate compared to their long-chain counterparts. Knowledge of their specific interactions and removal dynamics in complex matrices needs significant expansion.

Proposed Research Priorities

A comprehensive research framework should prioritize three integrated actions. First, a long-term research and full-scale pilot trials should be conducted to evaluate the efficacy and environmental impact of emerging solutions, including electrochemical and plasma-based systems. This should follow with the development of predictive models to simulate the scalability and operational challenges of selected technologies by incorporating variables such as water chemistry, temperature, and competing contaminants. An investigation of the chemical fate and ecological toxicity of secondary byproducts should be carried out through employing advanced analytical tools like mass spectrometry to identify and track degradation pathways.

4.1.2. Hybrid Approaches: Combining Strengths of Complementary Methods

Integrating multiple PFAS remediation techniques in hybrid systems can enhance removal efficiencies while mitigating the limitations of standalone methods. For instance, hybrid approaches could pair low-cost adsorption systems (e.g., GAC, ion exchange) with destructive technologies (e.g., oxidation, electrochemical systems).

Actionable Directions:

- Explore desorption-regeneration-destructive hybrids, where spent adsorbents are integrated with on-site oxidation to destroy PFAS and regenerate media.
- Investigate the combination of physical methods (e.g., ultrafiltration membranes) with catalytic or biological processes to enhance degradation of recalcitrant PFAS molecules.
- Optimize advanced treatment trains by targeting stage-wise contaminant removal, prioritizing energy efficiency and economic feasibility for smaller treatment sites or decentralized systems.

- Conduct system-level lifecycle assessments (LCAs) to quantify the trade-offs between hybridized technologies and assess their scalability for various geographic and socioeconomic contexts.

4.1.3. Developing Comparative Lifecycle and Economic Metrics

The Gap: Lack of Standardized Assessment Tools While numerous studies have emphasized lifecycle and economic impacts, the lack of standardized methodologies limits the comparability of findings. Discrepancies in energy use, carbon emissions, secondary waste, and cost reporting across studies challenge the development of broad policy recommendations.

Proposals for Standardization:

- Develop universal metrics for energy intensity, environmental burden, and cost analyses, ensuring uniformity in reporting methodologies.
- Leverage machine learning-based modeling tools to synthesize data across disparate studies, predict outcomes under varying scenarios (e.g., water chemistries, technology lifespans), and automate comparative LCAs.
- Collaborate globally on creating open-access databases that include PFAS chemical properties, treatment outcomes, and lifecycle figures, allowing researchers to benchmark results and build on existing studies.

4.1.4. Policy Implementation and Environmental Justice Considerations

As regulatory thresholds for PFAS concentrations in drinking water continue to evolve, gaps between policy requirements and technological availability hinder effective implementation.

Policy Implementation Gaps: Existing policies, such as EPA-enforced maximum contaminant levels, often mandate concentrations far below standard treatment capabilities. Municipal systems, particularly in underserved regions, may face significant financial and logistical barriers to achieving compliance.

Proposed Research and Policy Goals:

- Undertake cost-benefit analyses considering affordability in low-income communities and environmental impacts across regions.
- Advocate for streamlined funding channels that promote the adoption of high-efficiency methods in communities struggling with limited financial resources.
- Strengthen federal oversight and provide clearer guidelines on PFAS monitoring, treatment efficacy, and secondary waste disposal to align technology performance with regulatory goals.

Environmental Justice and Affordability: Strategies must account for differential impacts across communities, particularly those disadvantaged by systemic underinvestment or proximity to contamination hotspots. The cost of advanced treatment technologies may be prohibitive for many municipalities, raising equity concerns. Research can address these disparities by emphasizing technologies with low capital/operational costs and supporting affordable pilot programs in affected areas.

4.1.5. The Role of Public-Private Partnerships and Collaboration

Solving the PFAS crisis requires coordinated efforts between public agencies, private industries, and academic institutions. Public-private partnerships (PPPs) offer significant potential to distribute financial and operational burdens across stakeholders while fostering innovation.

Actionable Avenues for Collaboration:

- **Funding Mechanisms:** Governments should incentivize PPPs through grants, low-interest loans, and tax credits, allowing private companies to test high-risk but potentially high-reward technologies.
- **Data Sharing:** Foster collaboration through shared knowledge platforms that consolidate performance metrics, treatment costs, and regional case studies to guide decision-making.
- Promote private-sector investment in large scale demonstration projects, supported by government subsidies to reduce investor risk.

- Forge international collaborations to adapt globally successful technologies to region-specific regulatory and environmental climates.

7. CONCLUSION

The challenge of remediating per- and polyfluoroalkyl substances (PFAS) stems from their persistence, bioaccumulative nature, and extensive contamination of groundwater and surface water that pose risks to ecosystems and human health. Widely used technologies such as granular activated carbon (GAC) and ion exchange resins demonstrate high removal efficiencies for PFAS but generate secondary waste and perform less effectively with short-chain compounds or complex water chemistries. Membrane options like reverse osmosis and nanofiltration can remove over 99% of contaminants, but their use is restricted by high energy consumption and the need to manage concentrated brine wastes. Innovations in destructive technologies including electrochemical oxidation and plasma treatment offer the potential to mineralize PFAS with minimal secondary waste though they face challenges of high capital costs, considerable energy requirements, and scale-up for municipal or industrial purposes. Hybrid approaches that combine adsorption, chemical destruction, and biological methods may mitigate individual limitations. Adopting these technologies require further evaluation of lifecycle impacts and operational viability. Key knowledge gaps remain around the longevity and byproducts of these technologies as well as their economic feasibility in real-world settings. Addressing PFAS contamination is crucial for public health, with long-term exposures associated with cancer and immune dysfunction, and demands clear regulatory action and sustained investments in scalable remediation, especially for under-resourced communities. Industry must participate by developing PFAS-free products and investing in site-specific cleanup initiatives. Effective management depends on collaborative efforts involving scientists, engineers, policymakers, and stakeholders to design and implement sustainable, scalable, and equitable solutions, while leveraging tools like AI for enhanced monitoring and international data exchange. Ultimately, remediating PFAS requires a coordinated approach integrating technology, policy, and economic strategies to restore water safety and model best practices for future contamination events.

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