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Per- and Polyfluoroalkyl Substances (PFAS): History, Regulations and Strategies for the Removal

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Abstract: Per- and polyfluoroalkyl substances (PFAS) are a broad range of synthetic compounds that are widely used due to their high chemical resistance, hydrophobicity, and thermal stability. Those superior properties have also resulted in their designation as "forever chemicals" since they inherently show resistance to degradation in the environment. Hence, PFAS contamination has become a significant global concern for both ecological reasons and its adverse health effects to humans. This review highlights cornerstones in PFAS history along with global regulations that are applied in North America, Europe and Asia-Pacific region and current situation of Türkiye on PFAS utilization. Moreover, current PFAS removal and destruction technologies with their mechanisms, efficiencies, and limitations have been discussed. In terms of PFAS removal; advantages and disadvantages of adsorption, membrane filtration, advanced oxidation and thermal destruction strategies have been reviewed. Among others, activated carbon (AC) and ion exchange resins are classified as the two of the most investigated adsorbents for PFAS. Even though they are capable of effectively capturing long-chain PFAS, they are challenged by the removal of short-chain variants. Membrane filtration processes, such as nanofiltration (NF) and reverse osmosis (RO), could achieve high removal rates, but generation of concentrated brines that require further treatment is regarded as a task that should be solved. Advanced oxidation processes (AOPs), that include photochemical or electrochemical methods, could degrade PFAS; however, significant energy requirement and generation of hazardous byproducts could be regarded as a significant concern. Thermal desorption and high-temperature incineration, are effective for the complete destruction of PFAS; nevertheless, they necessitate strict controls to reduce secondary emissions. Emerging technologies, including plasma-based treatments, supercritical water oxidation, and novel catalytic systems have been developed to degrade PFAS; however, their scalability and cost-effectiveness are still restricted. Hybrid systems, which incorporate multiple techniques, are becoming more widely acknowledged as potential solutions to the constraints of individual methods.

Keywords: PFAS, Per- and polyfluoroalkyl substances, water contamination, PFAS remova.

Per ve Poliflorlu Alkil Maddeler (PFAS): Tarihçesi, Düzenlemeler ve Arıtma Stratejileri

Özet: Per- ve polifloroalkil maddeler (PFAS), yüksek kimyasal direnci, hidrofobik özellikleri ve termal stabiliteleri nedeniyle yaygın olarak kullanılan geniş bir sentetik bileşik yelpazesini temsil eder. Bu üstün özellikler, çevrede bozunmaya karşı doğal direnç göstermeleri sebebiyle “kalıcı kimyasallar” olarak adlandırılmalarına yol açmıştır. Bu nedenle, PFAS kirliliği hem ekolojik nedenler hem de insan sağlığı üzerindeki olumsuz etkileri nedeniyle önemli bir küresel endişe haline gelmiştir. Bu derleme, PFAS tarihindeki temel taşları, Kuzey Amerika, Avrupa ve Asya-Pasifik bölgesinde uygulanan küresel düzenlemeleri ve Türkiye'nin PFAS kullanımındaki mevcut durumunu vurgulamaktadır. Ayrıca, mevcut PFAS giderme ve yok etme teknolojileri, mekanizmaları, verimlilikleri ve sınırlamaları tartışılmıştır. PFAS giderilmesi açısından; adsorpsiyon, membran filtrasyonu, gelişmiş oksidasyon ve termal yıkım stratejilerinin avantajları ve dezavantajları gözden geçirilmiştir. Bunlar arasında, aktif karbon (AC) ve iyon değişim reçineleri, PFAS için en çok araştırılan adsorbanlardan ikisi olarak sınıflandırılmaktadır. Uzun zincirli PFAS'ı etkili bir şekilde tutabilmelerine rağmen, kısa zincirli varyantların giderilmesinde zorluklarla karşılaşılmaktadır. Nanofiltrasyon (NF) ve ters ozmoz (RO) gibi membran filtrasyon süreçleri yüksek giderim oranlarına ulaşabilse de, ileri işlemler gerektiren yoğunlaştırılmış tuzlu su üretimi çözülmesi gereken bir sorun olarak değerlendirilmektedir. Fotokimyasal veya elektrokimyasal yöntemleri içeren gelişmiş oksidasyon prosesleri (AOP'ler) PFAS'ı degrede edebilmektedir; ancak, önemli enerji gereksinimi ve tehlikeli yan ürünlerin oluşumu kayda değer bir endişe kaynağıdır. Termal desorpsiyon ve yüksek sıcaklıkta yakma, PFAS'ın tamamen yok edilmesi için etkili olmakla birlikte, ikincil emisyonları azaltmak adına sıkı kontrol önlemleri gerektirmektedir. Plazma tabanlı tedaviler, süperkritik su oksidasyonu ve yenilikçi katalitik sistemler gibi gelişmekte olan teknolojiler, PFAS'ı degrede etmek amacıyla geliştirilmiş olsa da, bu teknolojilerin ölçeklenebilirliği ve maliyet etkinliği hâlâ sınırlıdır. Birden fazla tekniği içeren hibrit sistemler ise, bireysel yöntemlerin kısıtlamalarına potansiyel çözümler olarak giderek daha fazla kabul görmektedir.

Anahtar Kelimeler: PFAS, Per- ve polifloroalkil maddeler, su kirliliği, PFAS giderimi.

Review Article

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1.History of PFAS

Per- and polyfluoroalkyl substances (PFAS) constitute a class of synthetically manufactured chemicals characterized by their unique fluorinated structures. Compounds in which all hydrogen atoms in the carbon backbone are fully replaced with fluorine are referred to as perfluoroalkyl substances. Conversely, when only a portion of the hydrogen atoms are substituted with fluorine, these compounds are classified as polyfluoroalkyl substances (Figure 1a). Furthermore, their molecular structures often incorporate functional groups such as carboxylic acids, sulfonic acids, amines, or other analogous moieties (Figure 1b).

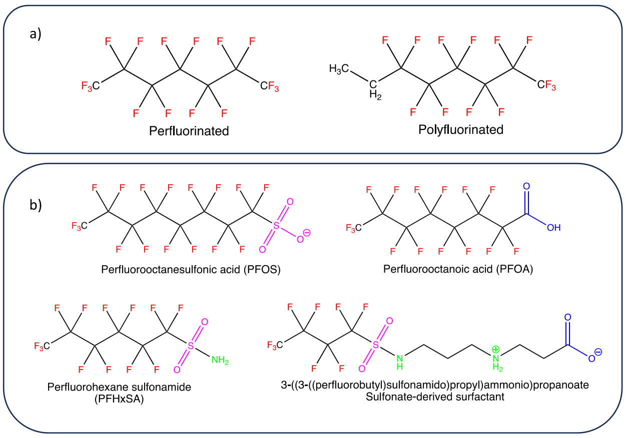
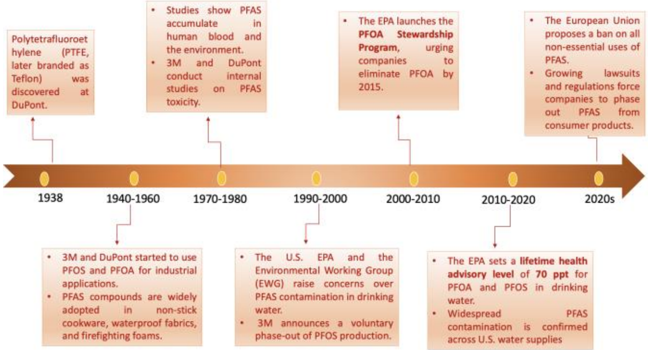


Figure 1. a) Chemical representation of per- and polyfluorinated compounds b) examples of commonly used PFAS.
Şekil 1. Şekil 1. a) Per- ve poliflorlu bileşiklerin kimyasal gösterimi b) yaygın olarak kullanılan PFAS örnekleri.

The substitution of C-H bonds with C-F bonds results in the formation of one of the strongest chemical bonds in organic chemistry, granting PFAS remarkable thermal and mechanical stability. Additionally, PFAS exhibit both lipophobic and hydrophobic characteristics due to the fluorine atoms in their main carbon chain. Furthermore, the incorporation of functional groups into their structures enables interactions with polar molecules (Figure 1b). Due to this chemical diversity, the exact number of PFAS molecules currently in use is not precisely known; however, it is estimated to be between 4,000 and 5,000 (Brendel et al., 2018; Simon et al., 2019).

Carbon tetrafluoride (CF_4), the simplest perfluorocarbon, was first synthesized in 1886. In 1938, Roy J. Plunkett, working at DuPont's Jackson Laboratory, discovered polytetrafluoroethylene (PTFE) while conducting commercial experiments with chlorofluorocarbon refrigerants. PTFE's unique properties facilitated its use in the Manhattan Project for the separation of UF_6 isotopes (Buck et al., 2011; Dams & Hintzer, n.d.). After this discovery, comprehensive research was conducted to synthesize additional PFAS compounds that exhibit resistance to extreme reaction and operating conditions. Major events in PFAS history has been summarized in Figure 2.

Oil- and water-repellent properties, along with the chemical and thermal stability and friction-reducing characteristics of fluorinated chemical structures, resulted in the extensive production of consumer and industrial products that incorporate PFAS. PFAS exhibit significant resistance to chemical and thermal degradation, making them highly valuable for industrial applications that involve extreme temperatures, pressures, or corrosive environments. PFAS are extensively used in multiple industries, including fast food packaging, non-stick cookware, mining, photography, paints, aerospace, medicine, automotive, construction, and electronics, as well as in consumer products like stain-resistant carpets, waterproof clothing, and firefighting equipment (Buck et al., 2011) (Figure 3).



Polytetrafluoroethylene (PTFE, later branded as Teflon) was discovered at DuPont.

- 3M and DuPont started to use PFOS and PFOA for industrial applications.
- PFAS compounds are widely adopted in non-stick cookware, waterproof fabrics, and firefighting foams.

- Studies show PFAS accumulate in human blood and the environment.
- 3M and DuPont conduct internal studies on PFAS toxicity.

- The U.S. EPA and the Environmental Working Group (EWG) raise concerns over PFAS contamination in drinking water.
- 3M announces a voluntary phase-out of PFOS production.

- The EPA launches the **PFOA Stewardship Program**, urging companies to eliminate PFOA by 2015.

- The EPA sets a **lifetime health advisory level** of **70 ppt** for PFOA and PFOS in drinking water.
- Widespread PFAS contamination is confirmed across U.S. water supplies

- The European Union proposes a ban on all non-essential uses of PFAS.
- Growing lawsuits and regulations force companies to phase out PFAS from consumer products.

Figure 2. Timeline of major events in the history of PFAS.
Şekil 2. PFAS tarihindeki önemli olayların zaman çizelgesi.

The thermal and mechanical stability of PFAS, combined with their resistance to degradation, unfortunately results in bioaccumulation in the environment and the human body. For that reason, the categorization of PFAS that are used in industry and the establishment of a uniform classification system are essential for examining their effects on health and the environment. In the early 2000s, the scientific community raised concerns about the long-term health effects of PFAS exposure, primarily due to their environmental persistence and bioaccumulative characteristics. In 2002, the Organization for Economic Co-operation and Development (OECD) conducted a hazard assessment for perfluorooctane sulfonic acid (PFOS), determining that it is "persistent, bioaccumulative, and toxic to mammalian species," and linking it to liver and thyroid cancer in rats (Environmental Protection Agency, 2002). The report emphasized an epidemiological association between PFOS exposure and bladder cancer in humans (Environmental Protection Agency, 2002).

Figure 3. Sources of PFAS.
Şekil 3. PFAS kaynakları.

More recent studies have identified epidemiological correlations between PFOS and elevated cholesterol levels, impaired glucose metabolism, increased body mass index, disrupted thyroid function, infertility, and a higher prevalence of attention-deficit hyperactivity disorder (ADHD) (Saikat, 2013). Research conducted by the U.S. Centers for Disease Control and Prevention (CDC) in 2003 detected PFOS in the blood serum of nearly the entire U.S. population (approximately 98%) (Calafat et al., 2007; Lewis et al., 2015). Data from nationally representative serum samples collected during 2013–2014 further revealed exposure to perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHxS) (Centers for Disease Control and Prevention., 2019). The blood levels of PFOS and PFOA decreased after major PFAS manufacturers in the U.S., including 3M and DuPont, the biggest PFAS manufacturers, voluntarily phased out production in the 2000s (Centers for Disease Control and Prevention., 2019). However, as of 2017, both substances were still detectable in the blood of many Americans (Centers for Disease Control and Prevention., 2019).

To reduce bioaccumulation, it has been hypothesized that decreasing the chain length of PFAS could facilitate their excretion from the human body. Consequently, shorter-chain alternatives such as perfluorobutane sulfonate (PFBS) with four carbon atoms and the ammonium salt of hexafluoropropylene oxide dimer acid (HFPO-DA, commercially known as GenX) have been introduced as replacements for the eight-carbon PFOA. However, draft toxicity assessments conducted by the U.S. Environmental Protection Agency (EPA, Washington, DC, USA) in 2018 revealed that GenX and PFBS also exhibit adverse effects on the kidneys, immune system, liver, reproductive system, and organ development (Environmental Protection Agency, 2018).

PFAS compounds exhibit a tendency to accumulate not only in the human body but also in the environment. Research conducted by Sunderland et al. in 2019 demonstrated the persistent presence of PFAS in various sources, including water supplies, seafood, and biomass used in agriculture (Sunderland et al., 2019). Furthermore, these substances accumulate in the systems of plants grown in PFAS-contaminated soils (Ghisi et al., 2019) and in the bodies of animals exposed to or consuming PFAS-contaminated water (Ahrens & Bundschuh, 2014). Their resistance to degradation and physiological filtration has earned them the nickname "forever chemicals" (Kotthoff & Bücking, 2018).

An industry survey conducted by Buck *et al.* (Buck et al., 2021) revealed that, out of the 4,700 PFAS registered with Chemical Abstract Services (CAS), only 256 are widely used commercially. The remaining PFAS may have less environmental significance but still possess the potential to persist in the environment. Publicly available health and toxicity studies cover only a limited subset of PFAS compounds. *Modern analytical technologies have thus far identified and quantified approximately 50–60 distinct PFAS structures (Buck et al., 2021).*

The number of studies on PFAS has significantly increased in recent years, as evidenced by the growing number of review and research articles published on the subject (Figure 4). This trend is primarily attributed to the rising scientific efforts since the early 2000s aimed at reducing PFAS exposure and developing regulations and chemical methods to remediate contaminated water sources.

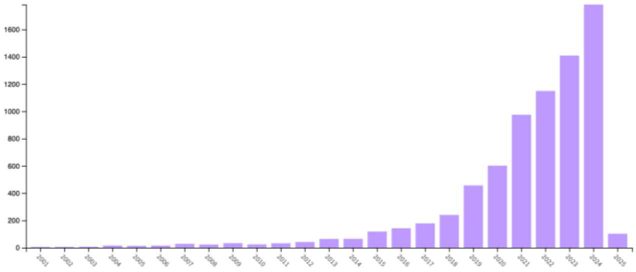


Figure 4. Yearly number of reports on PFAS according to the Web of Science database on January 30th, 2024.
Şekil 4. Şekil 4. Web of Science veri tabanına göre 30 Ocak 2024 tarihinde PFAS ile ilgili yıllık rapor sayısı.

Figure 5 illustrates the number of publications in different countries that include the keyword 'PFAS'. While United States is the leading country on PFAS research that mostly focus on determination of PFAS compounds and identification of their health concerns as well as removal strategies, there is also significant research in China, Canada and European Countries.

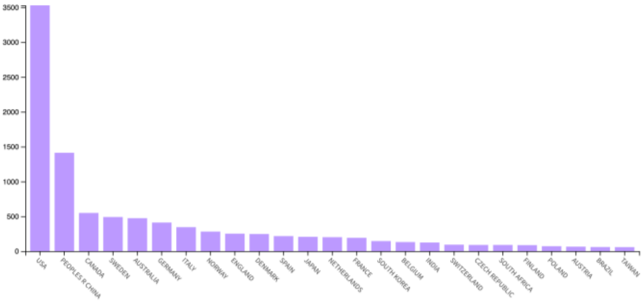


Figure 5. PFAS research in different countries according to the Web of Science database on January 30th, 2024.
Şekil 5. Web of Science veri tabanına göre 30 Ocak 2024 tarihinde farklı ülkelerdeki PFAS araştırmaları.

2. Global Regulations on PFAS Utilization

The regulation of PFAS is evolving rapidly as governments recognize the environmental and health risks associated with these chemicals. While some regions have implemented strict bans and restrictions, others are still in the early stages of developing regulatory frameworks. Global cooperation and harmonization of PFAS regulations will be crucial to ensure effective management and minimizing risks associated with these persistent chemicals.

In North America, United States and Canada have implemented regulations and restrictions on PFAS. In USA, EPA has introduced several initiatives, including the PFAS Strategic Roadmap (2021-2024), which aims to regulate PFAS through research, restriction, and remediation (U.S. Environmental Protection Agency [EPA], 2021). The Safe Drinking Water Act (SDWA) is being updated to include enforceable limits on certain PFAS compounds, such as PFOA and PFOS (U.S. Environmental Protection Agency [EPA], 2024). Additionally, the Toxic Substances Control Act (TSCA) requires manufacturers to notify the EPA of new PFAS-related activities (U.S. Environmental Protection Agency [EPA], n.d.). At the state level, numerous states, such as California and Maine, have banned PFAS in consumer products like food packaging and textiles (Bryan Cave Leighton Paisner, 2024). Canada has also implemented restrictions on PFAS under the Canadian Environmental Protection Act (CEPA) (Environment and Climate Change Canada, 2024). In 2021, the government proposed adding all PFAS to the Prohibition of Certain Toxic Substances Regulations, effectively banning their manufacture and use in most applications. Canada also monitors PFAS levels in drinking water and has set guideline values for specific compounds (Environment and Climate Change Canada, 2024).

The European Union (EU) has one of the most stringent regulatory frameworks for PFAS. Under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation, several PFAS substances have been restricted. In 2006, the sale of PFOS in Europe was restricted to only "essential uses," and by 2009, PFOS was added to the Stockholm Convention on Persistent Organic Pollutants (POPs) (Stockholm Convention., 2019). A decade later, at the Convention's ninth meeting, member countries agreed to ban the use of firefighting foams containing PFOA and to remove exemptions for PFOS use (Stockholm Convention, 2019). In

2023, five European countries (Denmark, Germany, the Netherlands, Norway, and Sweden) proposed a comprehensive PFAS restriction, which, if adopted, could phase out most uses of PFAS across the EU (European Chemicals Agency, 2024). Additionally, the Drinking Water Directive sets limits on PFAS concentrations in drinking water, and the Persistent Organic Pollutants (POPs) Regulation prohibits the use of certain long-chain PFAS (European Chemicals Agency, n.d.).

In Asia-Pacific region, China, as a major PFAS producer, has been gradually strengthening its regulatory framework. In 2020, the country included certain PFAS in its List of New Pollutants for Priority Management, restricting their production and use. Additionally, China has been expected to follow the Stockholm Convention on POPs, to phase out specific PFAS compounds like PFOS. However, the country continues to allow the use of PFAS in firefighting foams (Brennan et al., 2021). Japan regulates PFAS through the Chemical Substances Control Law (CSCL), which mandates risk assessments and restrictions on certain PFAS substances. The government has set drinking water guidelines for PFOA and PFOS and is considering further regulatory measures (EU-Japan, 2025). Australia follows a risk-based approach to PFAS management, primarily through the National PFAS Management Plan. The government has established drinking water guidelines and has been working on phasing out PFAS use in firefighting foams (National Health and Medical Research Council, n.d.).

A 2018 study by the International Pollutants Elimination Network (IPEN), involving 12 countries, revealed that while some countries complied with the Stockholm Convention by regulating PFOS, they lacked regulations for other PFAS compounds (International Pollutants Elimination Network, 2019). For instance, India became a party to the Stockholm Convention in 2006, but during the survey, it had no regulations or restrictions for any PFAS compounds (International Pollutants Elimination Network, 2019). In Sri Lanka, the prohibition of PFOS under the Stockholm Convention took effect in 2010, yet no measures were introduced for other PFAS substances (International Pollutants Elimination Network, 2019).

Türkiye has been actively aligning its regulations concerning PFAS with EU standards and also signed the Stockholm Convention on POPs on May 23, 2001, committing to take preventive and corrective actions regarding PFAS regulations. In November 2018, Türkiye enacted legislation to regulate POPs, including specific PFAS compounds. This law prohibits the manufacture, marketing, and use of certain substances, mandates emission reductions, and outlines waste management protocols. Notably, PFOS and its derivatives are restricted under this regulation (SGS, 2018). Additionally, Türkiye has updated its regulations in 2020 on food contact plastics to align more closely with EU standards. These updates include restrictions on specific substances, which may encompass certain PFAS compounds, to ensure consumer safety (Food Packaging Forum, 2020).

When analyzing PFAS-related research by country, the United States stands out as the dominant leader, producing significantly more studies than any other nation. China and several EU countries have also made substantial contributions to this field (Figure 5). In contrast, Türkiye has published relatively few studies on PFAS, with most focusing on the health effects of exposure. Moreover, Türkiye has yet to establish comprehensive regulations governing the production, use, and disposal of PFAS, highlighting a regulatory gap in managing these persistent chemicals.

3. Strategies for the Removal of PFAS

Despite restrictions on PFAS usage in several countries aimed at diminishing its consumption, it is still crucial to remediate contaminated areas, particularly water resources. Consequently, many technologies, including adsorption, membrane filtration, oxidation processes, thermal destruction, and bioremediation, have been developed to eliminate PFAS from water resources. The combination of methods, such as adsorption followed by oxidation, has shown improved efficacy in PFAS removal in specific cases.

3.1. Adsorption Techniques

Adsorption is regarded as one of the most prevalent and effective method for removing PFAS from contaminated water. This method depends on the affinity of PFAS molecules for different adsorbent surfaces, offering a versatile framework for addressing PFAS compounds (F. Li et al., 2020a; Rhakho et al., 2024).

3.1.1 Activated Carbon (AC)

Granular activated carbon (GAC) and powdered activated carbon (PAC) are the most common adsorbents utilized for the removal of PFAS (Ochoa-Herrera & Sierra-Alvarez, 2008a; Tan et al., 2023). They effectively capture long-chain PFAS, including PFOA and PFOS, owing to robust hydrophobic and electrostatic interactions with the carbon surface. Nonetheless, their efficacy declines significantly when addressing short-chain PFAS, which demonstrate lower adsorption affinities and a higher tendency to persist in solution. The underlying principle is that adsorption on activated carbon is largely driven by hydrophobic interactions and pore filling; thus, PFAS with longer perfluoroalkyl chains (more hydrophobic) are better adsorbed than those with shorter chains. Ross et. al also notes that adsorption mechanisms are strongly influenced by the PFAS chain length. The authors explain that long-chain PFAS, with their higher hydrophobicity, are more readily removed by AC, while short-chain PFAS are more challenging (Ross et al., 2018). This limitation requires regular replacement or regeneration of activated carbon, thereby raising operational costs and complexity (Tan et al., 2023).

3.1.2. Ion Exchange Resins

Ion exchange resins have emerged as a promising technology for the removal of PFAS, primarily through the use of anion exchange mechanisms. These resins are typically composed of a cross-linked polymer matrix functionalized with positively charged groups, such as quaternary ammonium moieties, which attract and bind negatively charged PFAS molecules like PFOA and PFOS. The removal process is driven by electrostatic interactions, where PFAS anions replace other anions that are originally associated with the resin. However, the approach's effectiveness is influenced by several factors. For example, competing ions and natural organic matter in the water may occupy exchange sites, reducing the resin's selectivity for PFAS. Additionally, variations in PFAS chain lengths impact adsorption efficiency, with shorter-chain compounds often being removed less effectively due to their lower hydrophobicity. To overcome these challenges, ongoing research is focused on optimizing resin design—such as modifying functional groups and pore structures—to enhance specificity and adsorption capacity for PFAS (Dixit et al., 2021; Ellis et al., 2025). Moreover, challenges including resin regeneration, disposal of used material, and potential fouling by co-contaminants in complex matrices restrict their scalability and long-term sustainability (Dixit et al., 2021).

3.1.3. Emerging Adsorbents

Recent advancements in materials science have introduced innovative adsorbents with enhanced performance for PFAS removal:

Molecularly Imprinted Polymers (MIPs): MIPs are engineered synthetic materials that mimic the selective binding properties of biological systems while offering greater stability and resilience. During their fabrication, a target PFAS molecule serves as a template, guiding the formation of specific binding sites that match the size, shape, and functional groups of the target compound. Once the template is removed, these polymers exhibit remarkable specificity, allowing them to selectively bind to PFAS molecules even in complex environmental matrices. Their robustness and precision make MIPs a promising tool for developing advanced strategies in PFAS remediation efforts (Olshansky et al., 2021).

Metal-Organic Frameworks (MOFs): MOFs are highly versatile crystalline materials characterized by their tunable pore structures, exceptionally high surface areas, and modular chemical functionality. These attributes enable MOFs to act as powerful adsorbents, capable of capturing and retaining a wide range of PFAS molecules with precision. The adjustable pore sizes and chemical groups in MOFs allow for the selective adsorption of both long-chain and short-chain PFAS, as well as emerging variants that are often more challenging to address with conventional methods. Furthermore, their structural flexibility enables researchers to design MOFs tailored for specific environmental conditions or PFAS profiles, making them an innovative and adaptable solution for advanced remediation technologies (Karbassiyazdi et al., 2023; R. Li, Alomari, Stanton, et al., 2021) .

While these emerging materials show great potential, challenges related to their cost, synthesis scalability, and environmental compatibility need to be addressed before the industrial utilization.

3.2. Membrane Filtration

Membrane-based technologies have gained significant attention as essential tools for the effective removal PFAS from water systems (Das & Ronen, 2022). These technologies employ multiple advanced mechanisms. First, size exclusion physically prevents PFAS molecules that exceed the membrane's pore size from passing through (Appleman et al., 2014; Banks et al., 2020; Franke et al., 2019; Tang et al., 2006);. Second, hydrophobic interactions leverage the natural affinity between the hydrophobic segments of PFAS molecules and the membrane material, enhancing retention (Wan et al., 2024). Finally, charge repulsion uses electrostatic forces to reject ionized PFAS, particularly those with a negative charge, thereby further reducing contaminant permeation (Zhi et al., 2025).

Such multifaceted mechanisms enable membranes to efficiently target a wide spectrum of PFAS, from long-chain compounds to their short-chain and emerging counterparts, even in complex aqueous matrices. Membrane-based systems, such as reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF), offer scalability, making them suitable for applications ranging from municipal water treatment facilities to industrial remediation processes. However, the generation of concentrated PFAS-rich brine as a byproduct necessitates additional management strategies, emphasizing the need for integration with complementary treatment technologies.

Reverse Osmosis (RO): RO is widely recognized as one of the most effective membrane-based technologies for the removal of PFAS, including both long-chain and short-chain variants (Tow et al., 2021). Its exceptional efficiency arises from the use of semi-permeable membranes with nanometer-scale pores, which create a barrier that permits the passage of water molecules while rejecting dissolved PFAS, other contaminants, and even ions. This process not only achieves high removal rates but also maintains broad applicability across diverse water matrices, including groundwater, surface water, and industrial effluents. However, the primary drawback of RO systems lies in the production of concentrated brine, a byproduct that contains PFAS and other co-contaminants in highly concentrated forms. This brine poses significant environmental and logistical challenges, as its treatment or disposal often requires energy-intensive processes, specialized infrastructure, or adherence to strict regulatory frameworks.

Nanofiltration (NF): (NF) operates similar to reverse osmosis (RO), utilizing semi-permeable membranes to separate contaminants from water. However, unlike RO, NF membranes feature slightly larger pore sizes, typically in the range of 1–10 nanometers, which significantly reduces the energy requirements and operational pressures needed for filtration. This distinction translates to lower operational costs and makes NF systems particularly appealing for applications where energy efficiency is a key consideration.NF membranes are highly effective in removing long-chain PFAS molecules and other larger organic and inorganic contaminants. The removal efficiency for long-chain PFAS compounds is attributed to their size and hydrophobic interactions, which allow the NF membrane to reject these molecules with minimal fouling or degradation over time. Additionally, NF membranes demonstrate robust performance in the removal of divalent and multivalent ions, contributing to their versatility in treating a variety of water sources, including industrial wastewater, municipal supplies, and surface water.

However, the efficacy of NF systems diminishes when dealing with short-chain PFAS, such as perfluorobutanoic acid (PFBA), which are characterized by smaller molecular sizes and lower hydrophobicity. These properties enable short-chain PFAS to pass through the NF membrane more easily, reducing the overall removal efficiency. Despite this limitation, NF remains a valuable option, particularly for applications that prioritize energy efficiency and cost-effectiveness over the comprehensive removal of all PFAS variants (Franke et al., 2021) .

Ultrafiltration (UF): UF is a membrane-based treatment technology widely utilized for its ability to remove larger particles, suspended solids, and macromolecules, such as proteins and polysaccharides, from water. Its membranes, which typically have pore sizes ranging from 0.01 to 0.1 microns, effectively capture these larger contaminants, However, due to their relatively large pore sizes, UF membranes are not capable of filtering out PFAS, which are much smaller and highly resistant to conventional filtration techniques.

Despite this limitation, UF plays a pivotal role as a pre-treatment stage in multi-step water remediation systems. By effectively removing particulates, organic matter, and microorganisms from the feed water, UF significantly reduces the fouling, clogging, and scaling risks that commonly affect downstream processes such as RO and NF. In other words, UF pretreatment could improve the operational efficiency and prolong the service life of RO and NF membranes, ultimately leading to lower maintenance requirements and reduced operational cost (Arkhangelsky et al., 2008).

While membrane-based approaches represent a cornerstone in PFAS remediation, challenges such as brine disposal, membrane fouling, and limited efficacy for short-chain PFAS persist. Research into hybrid systems that integrate UF, NF, and RO with other treatment technologies, such as advanced oxidation processes or adsorption, holds promise for addressing these limitations. Additionally, advancements in membrane material science, including the development of selective coatings or PFAS-specific functionalized membranes, may further improve separation efficiency and reduce operational drawbacks. Such innovations are essential to ensure the sustainability and practicality of membrane-based technologies in addressing the global PFAS contamination crisis.

3.3. Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes (AOPs) have garnered significant attention for their potential to degrade PFAS into less harmful by-products (Gao et al., 2021). Unlike conventional removal methods, which focus on separation or adsorption, AOPs aim to break the strong carbon-fluorine (C-F) bonds that characterize PFAS compounds, achieving their mineralization into end products like fluoride ions, carbon dioxide, and water. AOPs utilize highly reactive chemical species, particularly hydroxyl radicals (•OH) and sulfate radicals ($SO_4^{\bullet -}$), to initiate and sustain oxidative degradation (F. Li et al., 2020b).

Photochemical Oxidation: Photochemical methods, such as UV irradiation in combination with oxidants like hydrogen peroxide (H_2O_2) or persulfate, generate reactive radicals capable of attacking PFAS molecules. UV light facilitates the activation of these oxidants, producing species that disrupt the C-F bonds. While effective for some PFAS, this approach often requires high energy input and is limited by the need for prolonged exposure times and the potential generation of toxic intermediate products (Nzeribe et al., 2019; Umar, 2021).

Electrochemical Oxidation: Electrochemical methods use electrodes to drive oxidation reactions, either directly or via the production of oxidants such as hydroxyl radicals, ozone, or chlorine species. Electrochemical AOPs offer advantages in their ability to be operated on-site and scaled to varying treatment volumes. However, challenges such as electrode fouling, energy consumption, and the selective degradation of specific PFAS compounds persist. Innovations in electrode materials and system designs are being explored to enhance efficiency and applicability (Radjenovic et al., 2020).

Catalytic AOPs: Catalytic advanced oxidation processes (AOPs) represent a promising frontier in PFAS remediation, leveraging catalysts to enhance the generation and activity of reactive oxidative species. By introducing catalysts, these systems achieve greater efficiency in breaking the carbon-fluorine (C-F) bonds of PFAS, addressing challenges like high energy requirements and prolonged treatment times associated with traditional AOPs. Catalysts facilitate the decomposition of oxidants, such as hydrogen peroxide (H_2O_2) or persulfate, into potent radicals like hydroxyl radicals (•OH) and sulfate radicals ($SO_4^{\bullet -}$), which are key to the oxidative degradation of PFAS (Gar Alalm & Boffito, 2022).

Metal-Based Catalysts: Transition metals like iron (Fe), manganese (Mn), cobalt (Co), and copper (Cu) are commonly used as catalysts in Fenton-like and persulfate activation systems. Fe(II) and Fe(III) are widely employed in homogeneous and heterogeneous Fenton systems to activate H_2O_2, producing hydroxyl radicals that oxidize PFAS molecules. Cobalt-based catalysts are highly effective for activating persulfate to generate sulfate radicals, which exhibit superior selectivity and persistence in degrading recalcitrant PFAS compounds. However, metal-based catalysts can suffer from leaching, which may cause secondary contamination and necessitate post-treatment (Chen et al., 2015; Gar Alalm & Boffito, 2022).

Metal Oxides and Nanocatalysts: Metal oxides like titanium dioxide (TiO_2), manganese dioxide (MnO_2), and cerium oxide (CeO_2) are often used in photocatalytic systems. TiO_2, a well-established photocatalyst, exhibits excellent stability and activity under UV light but is limited by its narrow absorption spectrum. Efforts to expand its activity under visible light include doping with metals (e.g., silver or platinum) or non-metals (e.g., nitrogen or carbon). Nanostructured catalysts, such as zero valent iron nanoparticles or bimetallic systems, offer enhanced surface area and reactivity, improving degradation rates for PFAS with complex structures (Chen et al., 2015).

Carbon-Based Catalysts: Functionalized carbon materials, such as graphene oxide, carbon nanotubes, and biochar, are gaining attention for their ability to activate oxidants and adsorb PFAS simultaneously. These materials often exhibit high stability and tunable surface properties, making them effective in hybrid systems (Dey et al., 2024).

Emerging Catalysts: Recent advances in perovskite oxides, metal-organic frameworks (MOFs), and covalent organic frameworks (COFs) highlight their potential for PFAS degradation. These materials offer highly customizable structures, enabling precise control over catalytic activity and selectivity (R. Li, Alomari, Islamoglu, et al., 2021; Pala et al., 2023).

Current research has focused on developing more robust, recyclable catalysts and optimizing hybrid systems that combine catalytic AOPs with adsorption or membrane filtration. Additionally, exploring green and renewable energy sources, such as solar-driven photocatalysis, can improve sustainability and cost-effectiveness. Catalytic AOPs remain a cutting-edge solution for PFAS degradation, holding potential for widespread application as technology matures.

3.4. Thermal Destruction

The thermal decomposition of PFAS involves exposing contaminated materials to extreme temperatures (generally exceeding 1,000°C) in controlled conditions. This high-temperature environment disrupts the C-F bonds, the strongest bonds in organic chemistry, resulting in the complete breakdown of PFAS molecules. Thermal destruction techniques include incineration, plasma-based processes and pyrolysis.

Incineration: Incineration is a conventional approach involving the combustion of PFAS-containing materials in specialized incinerators, such as rotary kilns or fluidized bed systems. Effective destruction requires maintaining temperatures above 1,100°C, sufficient oxygen levels, and residence times to ensure complete mineralization. Unfortunately, the formation of toxic by-products like hydrogen fluoride (HF) or polyfluorinated intermediate compounds is inevitable during incineration (Altarawneh et al., 2022; Stoiber et al., 2020).

Plasma-based processes: Plasma treatment utilizes ionized gases at temperatures exceeding 5,000°C to achieve rapid and complete PFAS decomposition. The intense energy input breaks down PFAS molecules instantly, minimizing the risk of by-product formation. Plasma systems are particularly effective for concentrated PFAS wastes but can be energy-intensive and costly (Palma et al., 2022; Zhang et al., 2024).

Pyrolysis: Pyrolysis involves heating PFAS-containing materials in the absence of oxygen, resulting in thermal decomposition into simpler molecules. While pyrolysis can effectively degrade PFAS, the process often requires integration with secondary treatment steps to handle fluorinated by-products and ensure environmental safety (Sørmo et al., 2023) .

Thermal destruction presents several notable advantages and challenges in PFAS remediation. One of its primary benefits is its high efficiency, as it can achieve nearly complete mineralization of PFAS when appropriate conditions are maintained. Additionally, it offers a permanent solution by converting PFAS into inert products, thereby eliminating the risk of environmental re-release. The method's versatility allows it to be applied to various PFAS-containing matrices, including soils, sludges, and liquid wastes. However, the process is not without its challenges. The high temperatures required for PFAS destruction demand significant energy input, raising concerns about the associated carbon footprint and operational costs. Incomplete combustion or suboptimal conditions can lead to the production of toxic by-products, such as hydrogen fluoride (HF), which necessitate neutralization. Furthermore, the fluorinated by-products generated during the process can corrode reactor linings and other system components, increasing maintenance needs. Regulatory compliance also poses a challenge, as emissions must adhere to strict air quality standards. Future advancements in thermal destruction aim to address these challenges through the optimization of conditions, including temperature, residence time, and reactor design, to enhance efficiency and reduce by-product formation. Hybrid systems that integrate thermal destruction with adsorption or catalytic processes are being explored to improve scalability and energy efficiency.

4. Conclusion and Future Directions

PFAS represent a significant environmental and public health challenge due to their chemical stability, widespread use, and persistence in ecosystems. While their unique physicochemical properties have led to widespread industrial and commercial applications, they are now recognized as "forever chemicals" that pose serious risks due to their bioaccumulation and toxicity. This review highlights the historical context of PFAS, their global regulation, and the diverse range of remediation technologies, including adsorption, membrane filtration, advanced oxidation processes and thermal destruction.

Despite progress in understanding PFAS and developing removal strategies, several critical challenges remain. Current technologies are often energy-intensive, cost-prohibitive, or limited in scalability and specificity, particularly for short-chain and emerging PFAS compounds. Regulatory frameworks, while evolving, still lack uniformity across regions, and there is an urgent need for comprehensive policies that encompass the entire PFAS lifecycle, from production to disposal. Moreover, the environmental and health impacts of PFAS alternatives, such as GenX and PFBS, highlight the importance of assessing the risks associated with replacement compounds before widespread adoption.

Continued development of innovative and hybrid methods, such as integrating advanced oxidation with adsorption or membrane systems, could improve efficiency and cost-effectiveness. Materials science advancements, including PFAS-selective adsorbents and functionalized membranes, will play a crucial role in overcoming current limitations. Moreover, advancing catalytic AOPs and optimizing thermal destruction systems to minimize energy consumption, by-product formation, and environmental impact are critical for scalability.

Addressing the PFAS contamination crisis requires a multidisciplinary approach combining technological innovation, regulatory reform, and public awareness. By prioritizing sustainable remediation and prevention strategies, society can mitigate the long-term impacts of these persistent pollutants and pave the way for safer alternatives in industrial and consumer applications.

Conflicts of Interest

The author declares no conflict of interest

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