USC University of Southern California

Origin, Effects, and Removal Technologies of PFAS

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SAFE WATER FOR ALL NATIONS

S.W.A.N is an initiative started by Dr. Massoud Pirbazari of the University of Southern California focusing on the improvement of drinking water quality for all nations.

The goal of S.W.A.N is to provide comprehensive and visually-based information so that people can treat their water, and in turn, improve their health and well-being.

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Your comments and suggestions are appreciated.

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Thank you.

Background Information

- PFAS Family
- Structure of PFOA and PFOS
- PFAS History
- PFAS Map in the US
- PFAS Toxicity

PFAS Family

- Perfluoroalkyl substances and Polyfluoroalkyl substances are together known as the PFAS group. PFAS are a large, complex group of synthetic chemicals widely used by human society since the 1940s.
- PFAS, especially perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), were widely used throughout our society. They had been applied for surface protection products, paper, packaging and leather products, and many industrial usages, thanks to their stability and unique ability to repel oil and water.
- Chemically speaking, PFAS group has the properties of being hydrophobic and lipophobic, thermally and chemically stable, and persistent and bioaccumulative. This is because the carbon fluoride bonds in the fluorinated alkyl chains are one of the strongest chemical bondings in the world. See Figure 1 for their chemical structure.

Structure of PFOA and PFOS

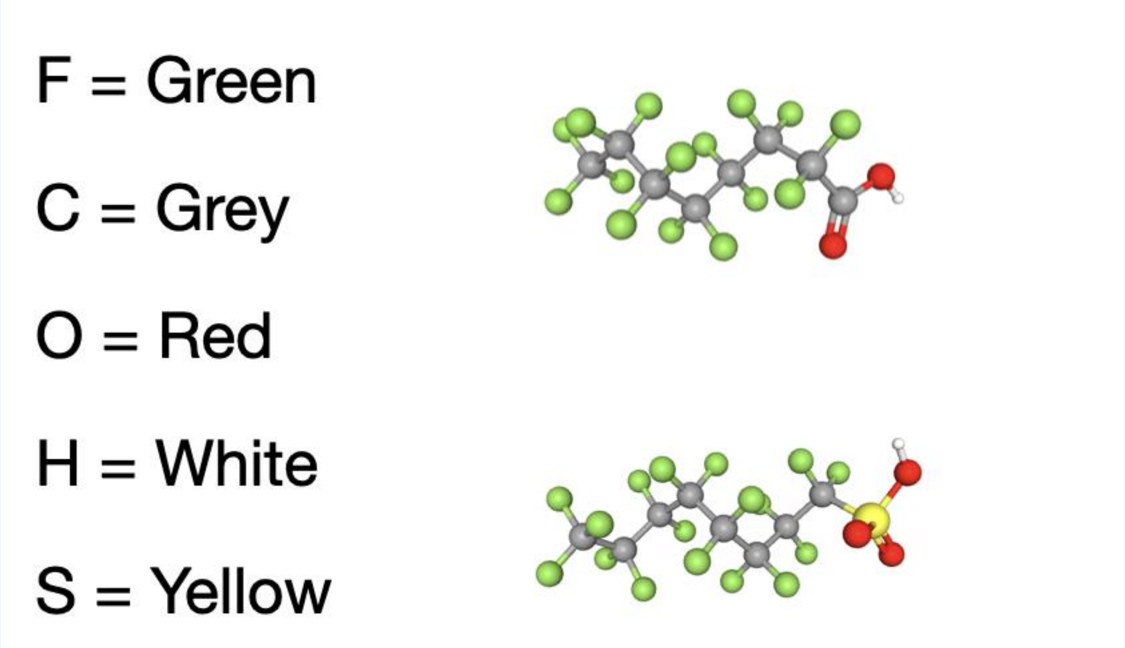

Figure 1: Structure of PFOA and PFOS in 3D [1][2]

PFAS History

- In 1934, the first member of the PFAS family, polychlorotrifluoroethylene (PCTFE), was discovered by Fritz Schloffer and Otto Scherer of the German chemical conglomerate, IG Farben.
- Then, in 1938, the chemical later known as Teflon was discovered by Roy J. Plunkett and Jack Rebok, which was used in the Manhattan Project as material for gaskets and valves holding uranium hexafluoride in pipes at the uranium plant.
- In 1953, another breakthrough in the PFAS family occurred when Patsy Sherman and Samuel Smith, chemists at 3M, discovered perfluorooctane sulfonate (PFOS).
- This compound, which would later gain recognition for its unique water- and oil-repellent properties, laid the foundation for the development of various stain-resistant and water-repellent products. Over time, PFOS became a cornerstone in the production of coatings, textiles, and firefighting foams, although its environmental persistence and health impacts would later lead to scrutiny and regulatory action [3].

PFAS History (cont’d)

- Primary U.S. manufacturers ceased using PFOA and PFOS in 2002 and phased out related chemicals by 2015. However, products containing these chemicals are still in stock and can still be used. Additionally, other PFAS chemicals are still in use, some of which are intended as replacements for PFOA and PFOS.
- Perfluorobutane sulfonate (PFBS) is a short-chain PFAS introduced as a replacement for PFOS in firefighting scenarios, but it shares the drawback of persistence and is possibly toxic [4]. GenX chemicals (such as hexafluoropropylene oxide, HFPO) were developed to replace PFOA in Teflon manufacturing and are said to be safer than PFOA.

PFAS History (cont’d)

- Today, PFAS substances can generally be found in drinking water, waste sites, firefighting foam, industrial applications, consumer products such as stain- or water-repellent and non-stick products, food packaging, biosolids, and food [5].
- The European Union began regulating PFAS earlier, with PFOS banned since 2009 and PFOA banned (also globally) since 2020 [6].

PFAS Map in the US

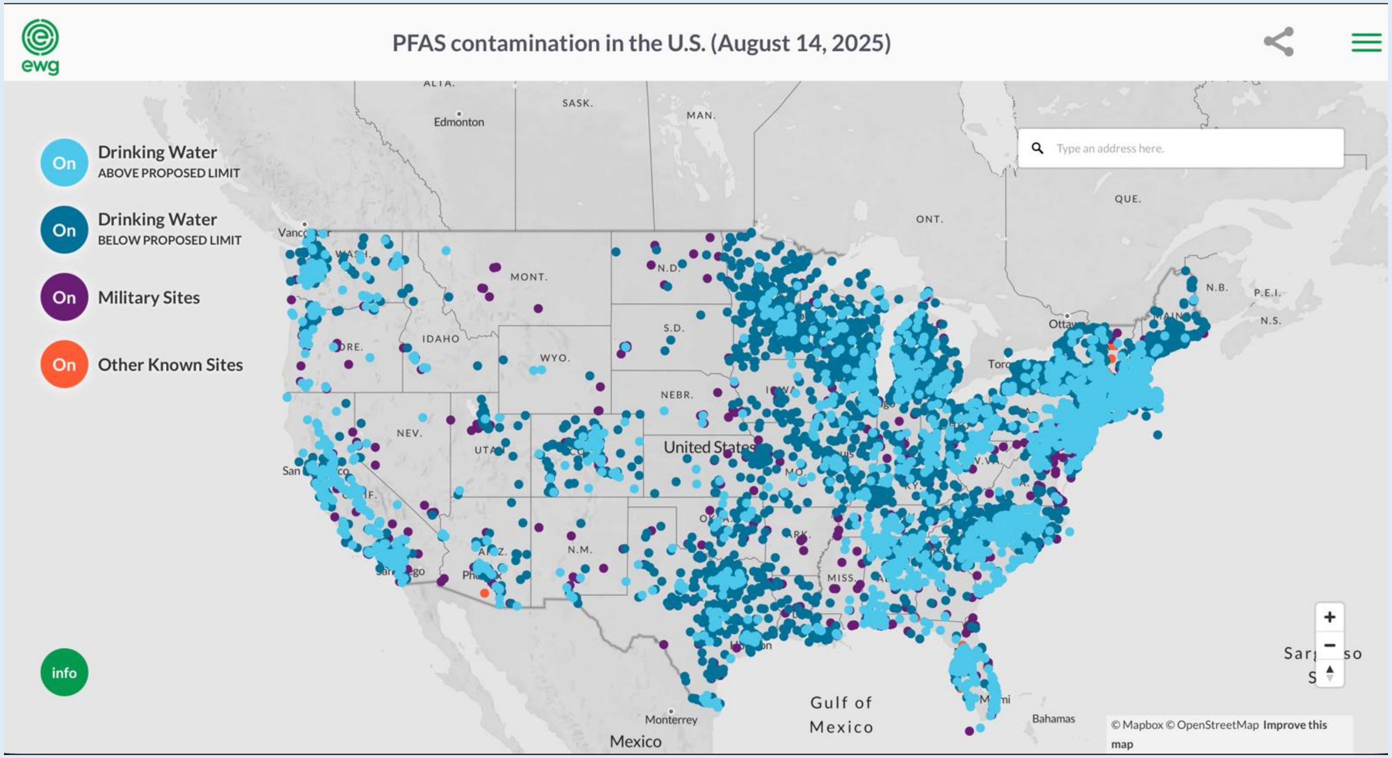

Figure 2: Map of PFAS in the United States on August 14, 2025 [7]

PFAS Toxicity

Due to the widespread presence of these substances, the problem of safety arises: with such frequent contact, how much exposure would result in sickness?

- The widespread use of PFAS substances over the last century, particularly PFOA and PFOS, has led to their persistent presence in our environment. These chemicals were commonly used in water pipelines, contributing to their lasting contamination in soil and drinking water.
- As a result, our food and water sources are at high risk of contamination, leading to long-term exposure to these toxic substances. Studies have shown that PFAS can accumulate in the human body, with researchers even detecting them in human blood.
- Many experiments had been taken on the potential toxicity of PFAS group on humans, which are generally conducted on other animals including laboratory rodents and zebrafish. Due to the fact that the time for PFAS to degrade is very long, the health implications of these substances might have a longer and deeper effect on human bodies.

PFAS Toxicity (cont’d)

- Extensive research has demonstrated that PFAS pose significant risks to human health and the environment due to their persistence, bioaccumulation, and toxicity. Epidemiological and toxicological studies link PFAS exposure to adverse outcomes including immunotoxicity, developmental and reproductive effects, liver damage, hormonal disruption, and increased risk of certain cancers. Even at low concentrations, long-chain PFAS (PFOA and PFOS) are particularly harmful, prompting global regulatory actions. Continued research is essential to understand the health impacts of emerging short-chain PFAS and mixtures, as well as to develop effective mitigation strategies.
- Experiments carried out on the animals mentioned before had made possible of certain potential effects PFAS accumulation and exposure can have on animals. These include hepatic and metabolic toxicity, reproductive and developmental toxicity, immunotoxicity, tumor induction, endocrine disruption, neurotoxicity, and obesity [8].

PFAS Toxicity (cont’d)

- It is also found that PFAS and microplastics are more toxic when combined. The study exposed water fleas to mixtures of PET microplastics plus PFAS compounds like PFOA and PFOS; the result: significantly greater toxic effects than from either substance alone. Observable effects included reduced birth rates, delayed development and sexual maturity, and stunted growth.
- About 40% of the increase in toxicity was due to a synergy between PFAS and microplastics (i.e. the combined effect is more than the sum of each alone); the rest was additive (just the combined independent effects) [9].
- Presence of PFAS can harm the human society in general and the environment. The studies on PFAS on plants, though only a little carried out, already pointed out that eating PFAS contaminated plants watered by contaminated water can cause human bodies to accumulate PFAS as well because plants are good absorber of anything contained in water and soil.

Current Solutions in Detecting PFAS

- Detecting PFAS Domestically
- Cited Methodology
- Detecting PFAS Commercially
- Detecting PFAS with Mass Spectrometry

Detecting PFAS Domestically

- Actions are already taken to phase out of PFAS usages and removal of PFAS residues in the environment. The latest happening in the United States being the actions of the Biden-Harris administration since 2021.
- The EPA has posted several Standard Analytical Methods to detect PFAS in drinking water, non-portable water and other environmental media, and air emissions.

Cited Methodology

“A 250-mL water sample is fortified with surrogates and passed through an SPE cartridge containing polystyrenedivinylbenzene (SDVB) to extract the method analytes and surrogates. The compounds are eluted from the solid phase sorbent with a small amount of methanol. The extract is concentrated to dryness with nitrogen in a heated water bath, and then adjusted to a 1-mL volume with 96:4\% (vol/vol) methanol: water and addition of the internal standards. A 10-\(\mu\)L injection is made into an LC equipped with a C18 column that is interfaced to an MS/MS. The analytes are separated and identified by comparing the acquired mass spectra and retention times to reference spectra and retention times for calibration standards acquired under identical LC/MS/MS conditions. The concentration of each analyte is determined by using the internal standard technique. Surrogate analytes are added to all Field and QC Samples to monitor the extraction efficiency of the method analytes.” [10]

Detecting PFAS Domestically (cont'd)

- In detection in drinking water, one method is to use Solid Phase Extraction and Liquick Chromatography/Tandem Mass Spectrometry [11] which is able to detect 18 members of the PFAS family including PFOS and PFOA.
- However, the standard methods of the EPA is impossible for regular households to use. MIT chemists recently invented a cheaper and faster way to test for PFAS as using a sensor based on lateral flow technology which many of us are familiar with as it is the same technology used in simple COVID-19 test suites [12].

Detecting PFAS Commercially

- Commercial solutions for detecting PFAS primarily rely on advanced analytical techniques, with LC-MS/MS systems being the gold standard for quantifying trace levels of PFAS in environmental and biological samples. These systems are often used in conjunction with solid phase extraction (SPE) kits—available from vendors like Waters, Agilent, and Phenomenex—to isolate and concentrate PFAS compounds prior to analysis. For broader detection of total fluorinated compounds, total organic fluorine (TOF) analyzers from companies like Mitsubishi and Analytik Jena offer complementary measurements. Field-deployable sampling systems, such as those by Eurofins and AquaVitas, facilitate on-site collection and preservation of samples for later lab analysis. Additionally, commercial laboratories including Eurofins, SGS, Pace Analytical, and ALS Global offer certified PFAS testing services for various matrices such as water, soil, food, and blood.

Detecting PFAS with Mass Spectrometry

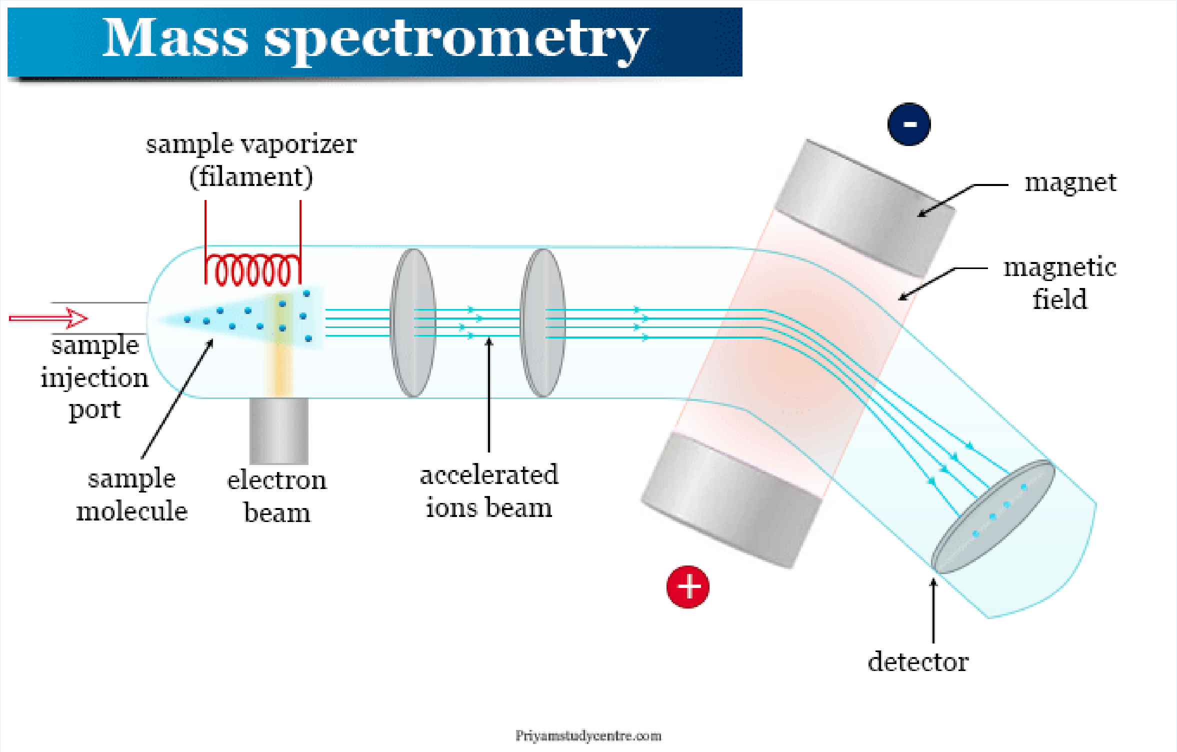

Figure 3: The method of using mass spectrometry to detect PFAS [13]

Current Solution in Removing PFAS

- Granular and Powdered Activated Carbon
- Anion Exchange
- High-pressure Membranes

Granular and Powdered Activated Carbon

- Activated carbon treatment, particularly granular activated carbon (GAC), is an effective and widely studied method for removing PFAS from drinking water. Its high porosity and large surface area make it a powerful adsorbent, effectively capturing longer-chain PFAS like PFOA and PFOS when used in a flow-through filter system. Factors such as the type of carbon, bed depth, flow rate, and water composition influence its efficiency. GAC has been successfully implemented in water treatment systems and can provide nearly complete removal of PFAS under optimal conditions, making it a reliable choice for long-term water purification.

Figure 4: GAC example [14]

Granular and Powdered Activated Carbon (cont’d)

- However, activated carbon treatment has limitations, particularly with shorter-chain PFAS like PFBS and PFBA, which do not adsorb as well. Additionally, powdered activated carbon (PAC), while similar to GAC, is less effective and not economical for PFAS removal. PAC’s small particle size prevents it from being used in flow-through filters, requiring it to be removed with sludge after treatment, which creates additional disposal challenges. The efficiency of activated carbon treatment also decreases over time as the material becomes saturated, necessitating regular replacement or regeneration, which adds to operational costs.

Anion Exchange

- Anion exchange treatment using ion exchange resins is an effective method for removing PFAS from water. These resins are made of tiny, porous polymer beads that act like magnets, attracting and holding contaminants. Anion exchange resins (AER) are positively charged, making them particularly effective at capturing negatively charged PFAS molecules and preventing them from passing through the water system.

Figure 5: Anion Exchange
Plant in Envirogen Group [15]

Anion Exchange (cont’d)

- While AER is highly effective, it is generally more expensive than granular activated carbon (GAC). A promising approach involves using AER in a single-use mode followed by incineration, which eliminates the need for resin regeneration. This method helps prevent the creation of additional waste streams, making it a cleaner and more efficient treatment option.

High-pressure Membranes

- Osmosis is the movement of water molecules across a semi-permeable membrane from an area of lower solute concentration to an area of higher solute concentration.
- High-pressure membranes, such as nanofiltration and reverse osmosis, are highly effective at removing PFAS, with studies showing over 90% removal efficiency, including for shorter-chain PFAS. Reverse osmosis provides even tighter filtration than nanofiltration, effectively rejecting nearly all salts and contaminants.

High-pressure Membranes (cont’d)

- These membranes allow for the removal of harmful particles while, in the case of nanofiltration, retaining beneficial minerals. Given their effectiveness, high-pressure membranes can be a powerful solution for ensuring clean drinking water, especially when applied at the household level where water treatment needs are smaller and more manageable.
- However, a significant drawback of this technology is the production of concentrated waste. Around 20% of the feedwater is retained as high-strength waste. Large-scale implementation may not be ideal due to the difficulty in handling this waste stream. For this reason, high-pressure membranes might be better suited for smaller-scale applications, such as residential use, where waste disposal is more controlled and less problematic.

High-pressure Membrane as a Means of Water Treatment

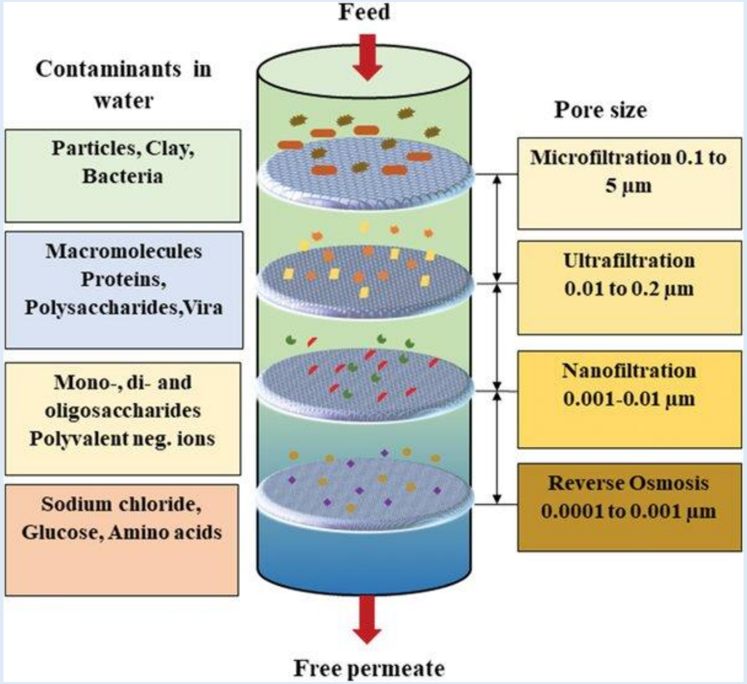

Figure 6: The process of using High Pressure Membranes in production [16]

Future Perspectives

- Biodegradation Studies
- Suggestions for Future Researches
- Future Research Technologies
- Installation of Regulations

Biodegradation Studies

- A study revealed that the mixture of PFAS and microplastics became mor toxic than either component in isolation.
- The persistence of PFAS to biodegradation is mainly attributed to the low chemical reactivity of the C-F bond.
- The nature and concentration of PFAS chemicals affect biodegradation ability and impact the biodegradation rate.
- An important factor in biodegradation is the physicochemical characteristic of the media and the nature of organic materials available, as well as the redox potential of the media.
- Temperature and pH affect enzymes and biochemical reactions; hence these factors affect the biodegradation of PFASs.
- The background organic content is an important factor for biodegradation as it serves as co-substrates and growth stimulants.

Suggestions for Future Research

Previous solutions for removing PFAS from drinking water, while effective in many scenarios, have notable problems that limit their practicality and scalability. Granular activated carbon (GAC), a widely used method, struggles with the adsorption of shorter-chain PFAS such as PFBS and PFBA. Over time, the efficiency of GAC declines as the material becomes saturated, necessitating frequent replacement or regeneration—both of which increase operational costs. The performance of GAC is also highly dependent on factors like the type of carbon used, bed depth, water flow rate, and overall water chemistry. Moreover, disposing of PFAS-laden carbon poses environmental and logistical challenges.

Suggestions for Future Research (cont'd)

- Powdered activated carbon (PAC) shares similar issues but introduces additional complications. Due to its small particle size, PAC cannot be used in flow-through filters and must instead be removed with sludge, generating secondary waste that is difficult to manage. Its lower effectiveness compared to GAC further reduces its viability as a long-term PFAS treatment option.
- Anion exchange resins (AER) offer improved performance for PFAS removal, especially for negatively charged compounds, but they come with higher costs. The resins often require regeneration, which creates waste brine that must be carefully handled. Although using AER in single-use mode followed by incineration can mitigate this, it still results in solid waste that needs responsible disposal. Additionally, large-scale applications of AER can be economically prohibitive due to the high cost of resin material.

Suggestions for Future Research (cont'd)

- High-pressure membrane technologies like nanofiltration and reverse osmosis are highly effective—even for short-chain PFAS—offering over 90% removal rates. However, these methods generate a concentrated waste stream, often comprising up to 20% of the treated water, which is difficult to dispose of safely and economically. These systems are also energy-intensive, expensive to operate, and prone to membrane fouling, which requires additional maintenance and pre-treatment. While well-suited for residential or small-scale use, they are less ideal for broader municipal application.

Future Research Technologies

Previous solutions for PFAS removal, while effective in certain contexts, face significant limitations in scalability and sustainability. Granular activated carbon (GAC) is widely used but struggles with shorter-chain PFAS such as PFBS and PFBA, and its efficiency declines as the material saturates, requiring costly regeneration or replacement. Powdered activated carbon (PAC) is less effective and generates sludge that is difficult to manage. Anion exchange resins (AER) provide better removal, especially for negatively charged PFAS, but are expensive and create brines requiring disposal. High-pressure membranes such as nanofiltration (NF) and reverse osmosis (RO) can remove over 90% of PFAS, including short-chain variants, but generate a concentrated waste stream and are energy intensive, with fouling and disposal issues further limiting large-scale application [17].

Future Research Technologies (cont’d)

Emerging technologies are shifting focus from removal to destruction of PFAS. Ultraviolet (UV) advanced reduction processes (ARPs), such as UV/sulfite, generate hydrated electrons capable of cleaving C--F bonds. In reverse osmosis concentrate, pretreatment with UV/persulfate followed by UV/sulfite achieved more than 90% defluorination within 24 hours [18]However, the process requires long treatment times and high energy inputs, and efficiency decreases in waters rich in dissolved organic matter. Advanced oxidation processes (AOPs) such as UV/persulfate or UV/H2O can partially degrade PFAS, but mineralization is incomplete and effectiveness depends strongly on water chemistry [19].

Future Research Technologies (cont’d)

Biological and enzymatic methods offer another pathway, though progress is limited. Enzymes such as laccases and peroxidases have shown partial defluorination in laboratory studies, but no system has achieved complete mineralization under environmental conditions. Major barriers include narrow substrate specificity, instability in complex matrices, and slow reaction rates [20]. Combining enzymatic treatments with chemical pretreatments may improve degradation, though enzyme inactivation and byproduct toxicity remain concerns. Similarly, hybrid approaches pairing AOPs with biologically active GAC have been proposed, but face challenges such as biofilm fouling and sensitivity to residual oxidants.

Future Research Technologies (cont’d)

Overall, hybrid and sequential strategies appear most promising. Membranes can effectively concentrate PFAS before destruction but require downstream treatment of brines. UV-based ARPs demonstrate high defluorination when combined with pretreatment, while enzymatic or biological polishing may complement chemical steps to manage intermediates. Yet all methods face trade-offs in cost, energy, and byproduct control. The current trajectory suggests that no single approach will suffice; instead, integrated treatment trains that balance removal, destruction, and sustainability will be necessary to manage PFAS contamination at scale.

Installation of Regulations

- These are the problems that future PFAS treatment solutions must overcome—offering high removal efficiency across all PFAS types, minimizing waste and operational complexity, and remaining cost-effective and scalable for both residential and large-scale use.
- In addition to improvements that should be made on methodology, potential updates on regulations should also be considered and implemented. As previously suggested, first world countries and certain developing countries such as China had already setup thorough regulation on reducing the use of PFAS overall and removal of PFAS in a period of time. However, as SWAN, we must also focus on such regulations to take place in less developed countries.
- Further actions should be taken on developing regulations at less developed countries. There are already international organizations such as BRICS helping where the more PFAS-regulated countries help the less regulated countries to form substantial regulation in reducing the use of PFAS.

Thank you for reading!

References

[1] National Center for Biotechnology Information (NCBI) PubChem, "Perfluorooctanoic acid," [Online]. Available: https://pubchem.ncbi.nlm.nih.gov/compound/Perfluorooctanoic-acid. [Accessed: Oct. 28, 2025].

[2] National Center for Biotechnology Information (NCBI) PubChem, "Perfluorooctanesulfonic acid," [Online]. Available: https://pubchem.ncbi.nlm.nih.gov/compound/Perfluorooctanesulfonic-acid. [Accessed: Oct. 28, 2025].

[3] Manufacturing Drive, "PFAS Industry Report," 2023. [Accessed: Sep. 16, 2025].

[4] Minnesota Dept. of Health, "Perfluorobutane Sulfonate (PFBS) and Drinking Water," 2022. [Accessed: Sep. 16, 2025].

References

[5] U.S. Environmental Protection Agency (EPA), "PFAS Explained," [Online]. Available: https://www.epa.gov/pfas/pfas-explained. [Accessed: Oct. 28, 2025].

[6] European Chemicals Agency (ECHA), "Per- and polyfluoroalkyl substances (PFAS)," 2025. [Accessed: Sep. 16, 2025].

[7] Environmental Working Group (EWG), "PFAS Contamination in the U.S. Map," 2025. [Accessed: Sep. 16, 2025].

[8] S. E. Fenton, A. Ducatman, A. Boobis, J. C. DeWitt, C. Lau, C. Ng, J. S. Smith, and S. M. Roberts, "Per- and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research," Environ. Toxicol. Chem., vol. 40, no. 3, pp. 606–630, 2021, doi: 10.1002/etc.4890.

References

[9] The Guardian, "PFAS and microplastics: A toxic combination threatening the environment," Nov. 25, 2024. [Accessed: Sep. 17, 2025].

[10] U.S. Environmental Protection Agency (EPA), "Reducing PFAS in drinking water: Treatment technologies," 2022. [Accessed: Sep. 16, 2025].

[11] H. Chen, Y. Li, and M. R. Hoffmann, "Photocatalytic transformation of per- and polyfluoroalkyl substances in aqueous environments," ChemSusChem, vol. 13, no. 15, pp. 3981–3998, 2020, doi: 10.1002/cssc.202000663. [Accessed: Sep. 17, 2025].

[12] Massachusetts Institute of Technology (MIT) News, "New sensor detects harmful 'forever chemicals' in drinking water," Mar. 11, 2024. [Accessed: Sep. 16, 2025].

References

[13] Priyam Study Centre, "Mass spectrometry: Principle," 2022. [Accessed: Sep. 16, 2025].

[14] L. Manoilova and K. Ruskova, "Active carbons and their functional applications in water purification – an overview," MATEC Web Conf., vol. 366, art. no. 04001, 2022, doi: 10.1051/matecconf/202236604001.

[15] Envirogren Group, "Ion exchange technology," [Online]. Available: https://www.envirogengroup.com/industrial-water-treatment-technologies/ion-exchange-technology/. [Accessed: Oct. 28, 2025].

[16] H. M. Mousa, H. S. Fahmy, G. A. M. Ali, H. N. Abdelhamid, and M. Ateia, "Membranes for oil/water separation: A review," Adv. Mater. Interfaces, vol. 9, no. 27, art. no. 2200557, 2022, doi: 10.1002/admi.202200557.

References

[17] T. Jin, M. Peydayesh, and R. Mezzenga, "Membrane-based technologies for per- and poly-fluoroalkyl substances (PFASs) removal from water: Removal mechanisms, applications, challenges and perspectives," Environ. Int., vol. 156, art. no. 106744, 2021, doi: 10.1016/j.envint.2021.106744.

[18] B. D. Fennell, S. Chavez, and G. McKay, "Destruction of per- and polyfluoroalkyl substances in reverse osmosis concentrate using UV-advanced reduction processes," Environ. Sci. Technol., vol. 58, no. 13, pp. 5414–5423, 2024.

[19] J. N. Uwayezu, I. Carabante, P. van Hees, P. Karlsson, and J. Kumpiene, "Validation of UV/persulfate as a PFAS treatment of industrial wastewater and environmental samples," J. Water Process. Eng., vol. 53, art. no. 103614, 2023, doi: 10.1016/j.jwpe.2023.103614.

References

[20] B. A. Harris, J. Zhou, B. O. Clarke, and I. K. H. Leung, "Enzymatic degradation of PFAS: Current status and ongoing challenges," ChemSusChem, 2024, doi: 10.1002/cssc.202401122.