DOE

MARKET RESEARCH STUDY

PFAS IN WASTEWATER

August 2023

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Table of Contents

1.0 Introduction to the Problem

According to EPA, in the United States approximately 34 billion gallons of wastewater are processed every day. At wastewater treatment plants, pollutants are removed including solid suspended particles, organic matter, nitrogen and phosphorous, various pathogens including bacteria, viruses and parasites, as well as chemicals and heavy metals. Once processed, the water is released back into local waterways for various uses such as drinking water, irrigation and sustaining aquatic life. A particular compound which has created great concern is a class of chemicals referred to as PFAS (per- and polyfluorakyl substances), which is \highly resistant to biodegradation. This report first introduces the complexity of the problem in order to set the stage for introducing current and emerging methods for potential PFAS destruction. Efforts have been made to give voice to the various constituents involved with this challenge including federal, state and local governments, wastewater treatment facilities and industry.

The overall purpose of this report is to introduce current and emerging methods for potential PFAS destruction

1.1. Background on PFAS

PFAS (per- and polyfluoroalkyl substances) refers to a class of over 12,000[1] synthetic chemicals, some of which have been used for decades to enhance a wide range of products. PFAS chemicals have applications in paints, non-stick cookware, stain-resistant products, pesticides, fast food packaging, photographic products, dental floss, firefighting foam, and other goods. PFAS are often called "forever chemicals," as they are highly resistant to biodegradation. Two of the oldest, most common, and widely studied PFAS — PFOS and PFOA — remain of concern, even though they were phased out of production in the U.S. in recent years.[2, 3]

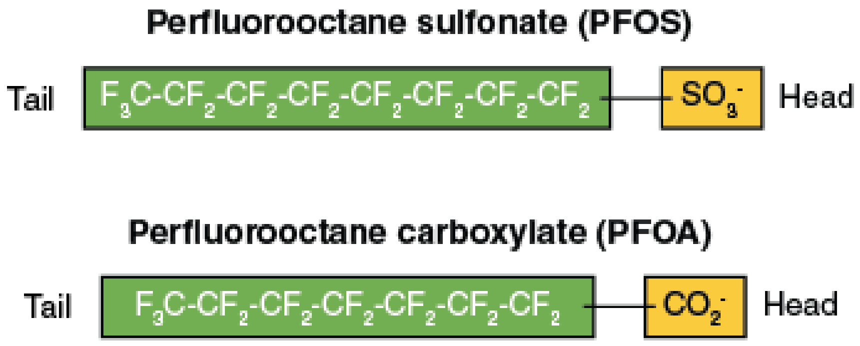


Figure 1: Structure of PFOS and PFOA Molecules

Source: ITRC[4]

Production and use of other PFAS continues, including newer formulations designed to be safer. While alternatives are being explored, years of PFAS use have led to PFAS accumulation in surface water, groundwater, wastewater, soil, air, and the bodies of fish, deer, and other wildlife. The U.S. Environmental Protection Agency (EPA) has indicated that PFAS can be harmful at the parts per trillion level. As time has gone on, the attention paid to detection, regulation, and remediation of PFAS has shifted from PFOS and PFOA — which drinking water systems were required to test for under the EPA's third Unregulated Contaminant Monitoring Rule (UCMR 3), issued in 2012 — to a broader array of PFAS found in the environment.

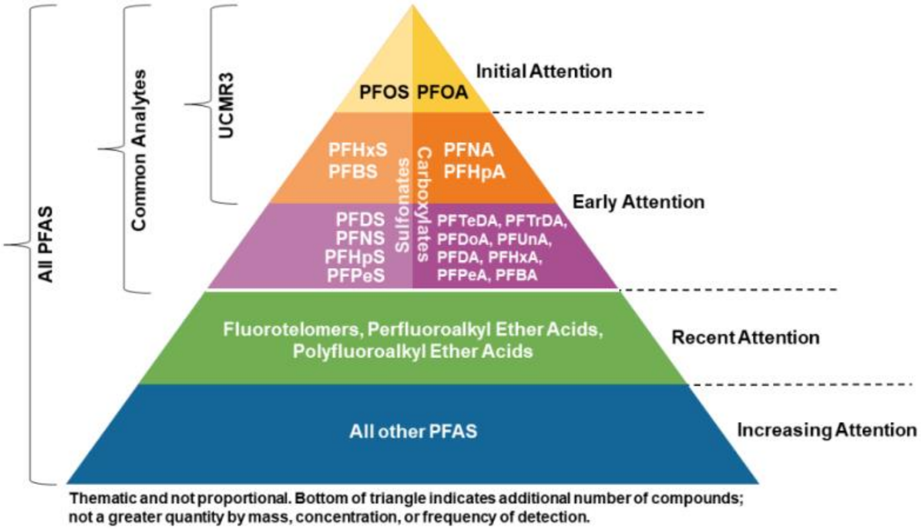
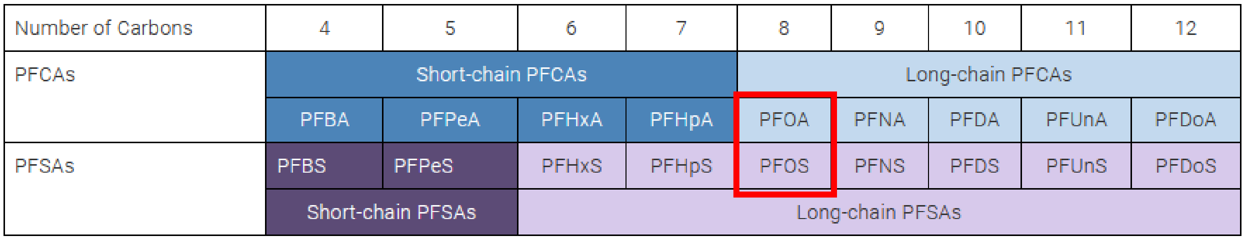


Figure 2: Shifting Attention to Different PFAS in the Environment

Source: J. Hale & P. Kleinfelder via ITRC[5]

PFAS exist in polymer and non-polymer varieties, the two main non-polymer types being the per- and polyfluoroalkyl substances in the name "PFAS." Within perfluoroalkyl substances or **perfluoroalkyl acids (PFAAs),** the two major subgroups are **perfluoroalkyl carboxylic acids (PFCAs)**, or perfluoroalkyl carboxylates, and **perfluoroalkane sulfonic acids (PFSAs)**, or perfluoroalkane sulfonates. These two groups of PFAS are among the most widely used and studied. PFAAs are often described as long-chain and short-chain PFAS because of their shared behaviors, which influence the associated health effects of exposure, persistence in the environment and the processes that can effectively break them down.[6]

Table 1: Short-chain and Long-chain PFAS (PFCAs and PFSAs)



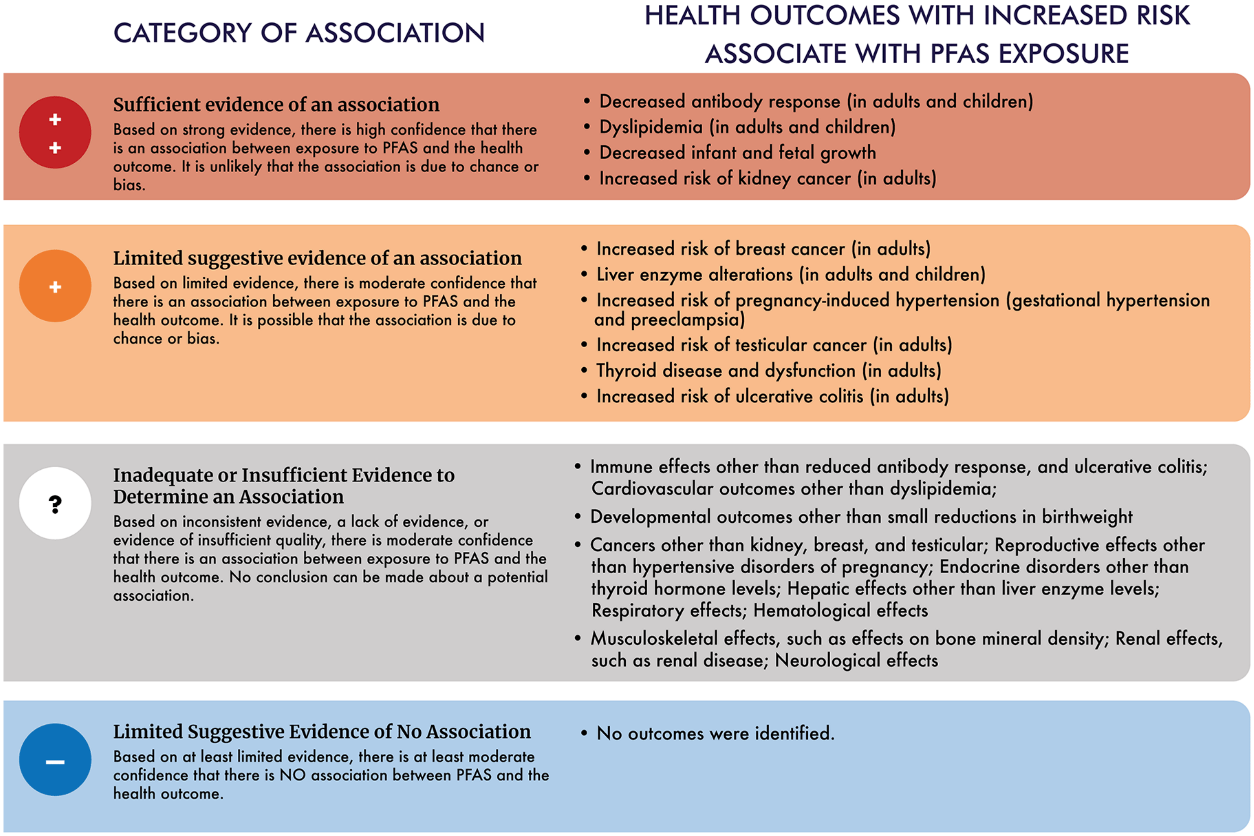
Number of Carbons	4	5	6	7	8	9	10	11	12
PFCAs	Short-chain PFCAs				Long-chain PFCAs				
	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUnA	PFDoA
PFSAs	PFBS	PFPeS	PFHxS	PFHpS	PFOS	PFNS	PFDS	PFUnS	PFDoS
	Short-chain PFSAs		Long-chain PFSAs						

Source: ITRC[7]

PFOA and PFOS are both considered long-chain PFAS. The short-chain, long-chain distinction is significant for both PFAS removal and destruction methods.

1.2. PFAS Toxicity and Extent of Drinking Water Contamination

Serious and diverse health effects have been linked to PFAS exposure, including compromised immune system (e.g., reduced vaccine efficacy); high levels of cholesterol; heart, liver, and thyroid disease; decreased fertility; low birth weight; preeclampsia in pregnant women; and kidney, liver, and testicular cancer.[8, 9, 10, 11, 12] The chart below shows the National Academies of Sciences, Engineering, and Medicine's evaluation of available evidence linking specified health outcomes to PFAS exposure. The summary is part of the National Academies' [consensus study report on PFAS exposure, testing, and clinical follow-up](), published in 2022.



CATEGORY OF ASSOCIATION	HEALTH OUTCOMES WITH INCREASED RISK ASSOCIATE WITH PFAS EXPOSURE
++ **Sufficient evidence of an association** Based on strong evidence, there is high confidence that there is an association between exposure to PFAS and the health outcome. It is unlikely that the association is due to chance or bias.	• Decreased antibody response (in adults and children) • Dyslipidemia (in adults and children) • Decreased infant and fetal growth • Increased risk of kidney cancer (in adults)
+ **Limited suggestive evidence of an association** Based on limited evidence, there is moderate confidence that there is an association between exposure to PFAS and the health outcome. It is possible that the association is due to chance or bias.	• Increased risk of breast cancer (in adults) • Liver enzyme alterations (in adults and children) • Increased risk of pregnancy-induced hypertension (gestational hypertension and preeclampsia) • Increased risk of testicular cancer (in adults) • Thyroid disease and dysfunction (in adults) • Increased risk of ulcerative colitis (in adults)
? **Inadequate or Insufficient Evidence to Determine an Association** Based on inconsistent evidence, a lack of evidence, or evidence of insufficient quality, there is moderate confidence that there is an association between exposure to PFAS and the health outcome. No conclusion can be made about a potential association.	• Immune effects other than reduced antibody response, and ulcerative colitis; Cardiovascular outcomes other than dyslipidemia; • Developmental outcomes other than small reductions in birthweight • Cancers other than kidney, breast, and testicular; Reproductive effects other than hypertensive disorders of pregnancy; Endocrine disorders other than thyroid hormone levels; Hepatic effects other than liver enzyme levels; Respiratory effects; Hematological effects • Musculoskeletal effects, such as effects on bone mineral density; Renal effects, such as renal disease; Neurological effects
− **Limited Suggestive Evidence of No Association** Based on at least limited evidence, there is at least moderate confidence that there is NO association between PFAS and the health outcome.	• No outcomes were identified.

Figure 3: Summary of Health Outcomes Associated with PFAS Exposure

Source: National Academy of Sciences (2022)[13]

While the Center for Disease Control's (CDC's) Agency for Toxic Substances and Disease Registry (ATSDR), U.S. Environmental Protection Agency (EPA), National Academy of Sciences, and other government bodies and researchers have identified these possible health risks, there is little or no toxicity data on most of the thousands of PFAS substances in existence. Current research has only focused on a smaller, well-known pool of PFAS variants. Another moving variable for study is the different kinds of exposure faced by humans at different points in their lives. In addition, PFAS can be hard to trace, as the types of chemicals and uses change over time, which makes assessing their health effects more difficult. More data are needed to better understand the connections between different PFAS and PFAS mixtures and health outcomes.[14, 15]

Given the links between PFAS and the adverse health outcomes listed above, contamination of drinking water is a major concern and the focus of testing, regulation, and legislation. The map below shows the extent of PFAS contamination of drinking water systems in the continental U.S.

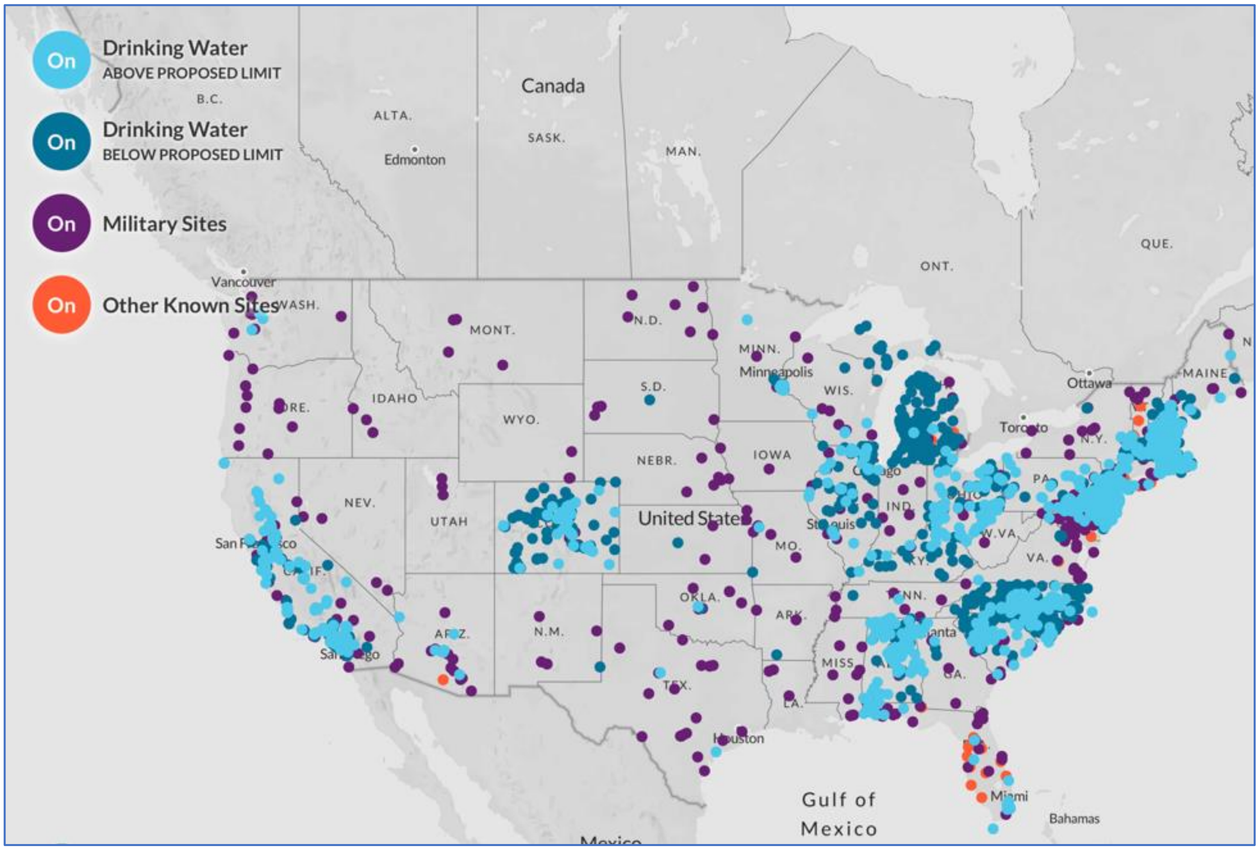


Figure 4: PFAS Contamination of Drinking Water in the U.S. (June 8, 2022)
Source: Environmental Working Group (EWG)[16]

The EPA's actions thus far have prioritized PFAS testing and regulation for drinking water.[17] The proposed PFAS National Primary Drinking Water Regulation (NPDWR), released in March 2023, is perhaps the best example. As the water treatment organization NACWA (National Association of Clean Water Agencies) states, the proposed drinking water regulations "will also impact wastewater and water recycling utilities primarily regulated under the Clean Water Act, particularly those that discharge to surface waters designated as drinking water supplies or to surface waters that overlie groundwater used or designated as drinking water supplies."[18]

1.3. Wastewater Treatment Plants and PFAS

There are more than 15,100 publicly owned wastewater treatment plants (WWTPs) in the U.S.,[19] providing wastewater services and treatment to over 75% of the population.[20] These WWTPs process 25–62.5 billion gallons per day[21, 22] of raw liquid influent from municipal wastewater, industrial wastewater, and landfill leachate. Untreated water entering WWTPs often contains elevated levels of PFAS. Now, as PFAS has been detected in drinking water in the U.S., water treatment facilities are increasingly expected to test for and remove PFAS from the water they process. The expectation is that the

WWTPs will also find ways to destroy PFAS completely, so it does not end up back in the water cycle. Yet, some studies have found higher concentrations of PFAS in treated wastewater effluent than in the raw influent. This is thought to be due to the wastewater treatment's biological and physical processes converting precursor compounds to terminal PFAS. That effluent may well end up in the aquatic environments (marine and freshwater) through the direct release of treated water.[23]

In the water treatment process, PFAS is first physically removed. Current physical methods for PFAS removal include **GAC (granular activated carbon), IX (ion exchange), reverse osmosis, and nanofiltration**.[24] These methods produce residuals, such as biosolids or spent filtration media, that has historically often been landfilled or used as fertilizer or incinerated at high temperatures. Incineration is the destruction (mineralization) of chemicals using heat.[25] The use of a sewage sludge incinerator (SSI) to destroy PFAS is very energy intensive. Data indicate that incineration also does not completely destroy PFAS.

The U.S. Environmental Protection Agency (EPA) has identified more than 12,000 PFAS chemicals and reports that many remediation solutions destroy some but not all.[26] Additionally, the incineration process has been found to result in PFAS emissions into the air.[27] For this reason, the Department of Defense recently banned incinerating PFAS-containing items, including firefighting foam.[28]

Wastewater Treatment Maintenance and Retrofitting Costs

According to the American Society of Civil Engineers (ASCE), most of the country's wastewater treatment plants (WWTPs) were built in the years surrounding the passage of the Clean Water Act (1972). These treatment plants were designed to last an average of 40-50 years. As WWTPs reach the end of their service lives, higher repair and maintenance costs are incurred. ASCE's 2021 Report Card for America's Infrastructure indicates that in the U.S., WWTPs operate on average at 81% of their design capacity, while about 15% are operating at or above capacity.[29] This leaves limited flexibility to accommodate wetter-than-average weather or longer treatment times due to added treatment processes.

The cost of wastewater treatment plant improvement projects varies. For example, the improvement project for the Bird Island Wastewater Treatment Facility in Buffalo, NY was announced as a $55 million project in 2022,[30] while a sewage treatment plant project in Broome County, NY was forecast to cost $275 million in 2018.[31] A report released by Minnesota's Pollution Control Agency in May 2023 estimated that it will cost municipal wastewater treatment plants between $2.7 million and $18 million per pound (depending on facility size) over a 20-year period to retrofit facilities and remove and destroy PFAS from municipal wastewater.[32]

1.4. U.S. Federal Government Driving New PFAS Destruction Technology

The Role of the United States Environmental Protection Agency and the States

The EPA plays a crucial role in the standards, regulations, policies, and research behind PFAS and the advancement of its destruction. At the same time, states and municipalities have the authority to instate their own regulations for clean water standards and PFAS elimination and have been at the forefront of PFAS control efforts. This dynamic is outlined below.

The Environmental Protection Agency (EPA), as well as states and municipalities, are at the forefront of PFAS control efforts.

The Clean Water Act of 1972 (CWA) grants the United States Environmental Protection Agency (EPA) the authority to address water pollution in multiple ways. Two of these are the authority to control the use or disposal of sewage sludge and biosolids and the regulation of industry discharges to surface water.[33, 34] First, the CWA requires the EPA to institute requirements governing the disposal of biosolids. These regulations, which apply to biosolids that are incinerated, applied to land, or disposal at a landfill, are put forth in 40 CFR Part 503.[35] To date, there is no federal regulation of PFAS in biosolids,[36, 37, 38] but in line with EPA's 2021 PFAS Strategic Roadmap, the agency plans to complete its risk assessment of PFOA and PFOS contamination of biosolids by the end of 2024.[39, 40] It has been left to the states thus far to address PFAS pollution through the disposal of biosolids.[41, 42]

Second, under the CWA, the EPA's National Pollutant Discharge Elimination System (NPDES) permitting program puts limits on discharges (effluent) from industry and from wastewater treatment plants. These are called **effluent limitations guidelines** and **pretreatment standards (ELGs)**.[43] The NPDES program is one of the levers the EPA is using to address PFAS contamination of water sources.[44] In the EPA's final Effluent Guidelines Program Plan 15 (Plan 15), released in January 2023, the EPA announced its determination that an ELG update is necessary for PFAS in landfill leachate discharges and that it is undertaking a publicly owned treatment works (POTW) **Influent PFAS Study** to gather data on industrial PFAS discharges to treatment plants across the country. This will enhance available data on PFAS in wastewater and help determine what further control measures may be needed at the sources.[45, 46, 47]

The term "***influent***" refers to the flow of wastewater or other liquid into a reservoir, basin, treatment process or treatment plant.

The EPA works to develop better PFAS analytical methods, PFAS effluent guidelines, and PFAS water quality criteria. EPA issued recommendations in December 2022 to the 47 states that are authorized to administer their National Pollutant Discharge Elimination System (NPDES) programs for publicly owned treatment works (POTWs) and industry discharges.[48] The EPA encourages states to use the NPDES program to control PFAS contamination by instituting supplementary permitting requirements recommended by EPA, specifying PFAS testing methods for discharged water, and so on.[49, 50] Some of the additional measures for limiting PFAS discharge implemented by individual states are discussed below in section 4.0. The EPA provides links to PFAS resources from individual states, which can be found here.

Additional organizations and non-profits that are important for national and state initiatives are the American Water Works Association (AWWA), National Association of Clean Water Associations (NACWA), U.S. Water Alliance, American Chemistry Council (ACC), and Water Research Foundation (WRF), which is a leading producer of research on PFAS in water. More information about the research conducted by the EPA will be found in the body of this report but can also be explored on the organization's webpage for Research on Per- and Polyfluoroalkyl Substances (PFAS).

Recent Federal Efforts

To develop a whole-of-government strategy to address the Nation's PFAS problem, the Executive branch and U.S. Congress directed an Interagency Working Group (IWG) to coordinate Federal research on PFAS through the **National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2021**.[51] The PFAS Strategy Team (PFAS ST) was formed to coordinate interagency PFAS research and development activities and support the development and implementation of the PFAS strategic research plan. PFAS Strategy Team members are subject matter experts from these Federal departments and agencies: USDA, SBA, EPA, DOE, DHS, NOAA, NASA, NSF, VA, DOT, EOP/OMB, DOC/NIST, CPSC, USGS, DoD, and HHS (HHS/NOH/NIEHS, HHS/CDC/ATSDR, HHS/FDA. [52]

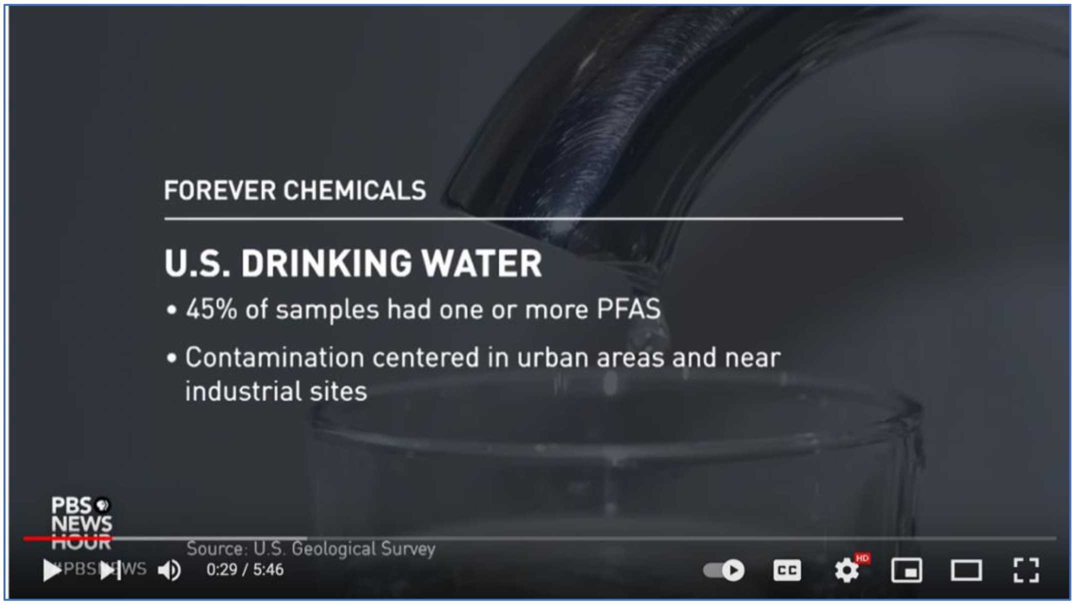
THE PFAS ST was directed to identify all currently federally funded PFAS research and development, the scientific and technological challenges that must be addressed, and identify solutions to the problem. Regarding solutions, the team was directed to identify safer alternatives to PFAS, identify methods to remove PFAS from the environment, and identify methods to degrade and destroy PFAS.[53]

In addition to the efforts of the PFAS ST, the Office of Science and Technology Policy (OSTP) issued this Request for Information (RFI): Request for Information; Identifying

Critical Data Gaps and Needs To Inform Federal Strategic Plan for PFAS Research and Development, to receive public comment.[54] In September 2022, the responses to this RFI were made public in RFI Response: Federal Strategic Plan for PFASs, July 2022.

In March 2023, both these efforts resulted in the publication of a state of the science report that discusses gaps and opportunities for the Federal Government to consider in developing a Federal PFAS strategy. Regarding PFAS removal and destruction, the Per- and Polyfluoroalkyl Substances (PFAS) Report includes an overview of the different treatment processes and technologies for removal and destruction of PFAS from water, solids, and air media, including a discussion of the readiness level, challenges, and research needs.

The sections that follow discuss the wastewater treatment process in general and regarding PFAS, current methods of PFAS containment used by wastewater treatment plants, state initiatives and regulations, and themes in recent PFAS destruction research, before closing with a survey of industry solutions that are either on the market or in the process of commercialization.



FOREVER CHEMICALS

U.S. DRINKING WATER

- 45% of samples had one or more PFAS
- Contamination centered in urban areas and near industrial sites

Source: U.S. Geological Survey

Follow this link to access video

Figure 5: Study Estimates That Nearly Half of the U.S. Drinking Water Is Contaminated

Source: PBS NewsHour[55]

2.0 Wastewater Treatment Process

Wastewater intended for reuse can come from a variety of places, such as stormwater, municipal wastewater, agriculture runoff and return flows, industry process and cooling water, as well as produced water derived from natural resource extraction. "Fit-for-purpose specifications" are used to ensure treatment processes yield the quality necessary for next use, which can span potable water supplies, industrial processes, agriculture and irrigation, groundwater replenishment, and environmental restoration.[56]

2.1. Wastewater Treatment Plant Process

Wastewater treatment processes, specifically processes that result in safe drinking water, can differ among water treatment plants. These steps often include **coagulation, flocculation, sedimentation, filtration, and disinfection**.[57]

Coagulation adds positively charged chemicals, such as aluminum, certain varieties of salts, or iron to the water to neutralize the negative charge from particles and dirt found in the water. This process creates larger particles. Flocculation mixes the water and creates even larger particles that are referred to as flocs. Depending on the plant, more chemicals will be added during this process.[58]

Sedimentation is the process of separating the water from solids, so the flocs sink to the bottom of the water. This process leads to filtration, which then leads to further separation between the remaining solids and clear water. Water is streamed through filters made from material like charcoal, sand, and gravel. The filters are various sizes and remove things like bacteria, chemicals, dust, viruses, and dust. Activated carbon filters are also used for the removal of unpleasant smells. Sometimes ultrafiltration or reverse osmosis can be used. Ultrafiltration can be used on its own or in combination with conventional filtration practices where water is streamed through a filter with tiny pores that only lets small molecules like salt and charged molecules through with the water. Reverse osmosis is often used for recycled water or salt water that will be used for drinking water. During this step, further particles are removed.[59]

At this point, chemicals are added to the water for disinfection. Types of chemicals used in this step are chlorine, chlorine dioxide, and chloramine. Before water is released from the plant, chemical levels are checked to ensure safe levels. The low disinfectant that is still present in the water when it leaves the plant is used to eliminate germs residing in the pipes between a water tap and a treatment plant. Another potential method for disinfection, which can be supplemental or used on its own, is ultraviolet light. A downside to ultraviolet light is that there aren't any chemicals continuously protecting the safety of the water as it travels in pipes after leaving a plant. After disinfection, a water treatment plant may put fluoride in the water and adjust the pH to make the taste better and help mitigate pipe breakdown.[60]

This process is illustrated in the following chart:

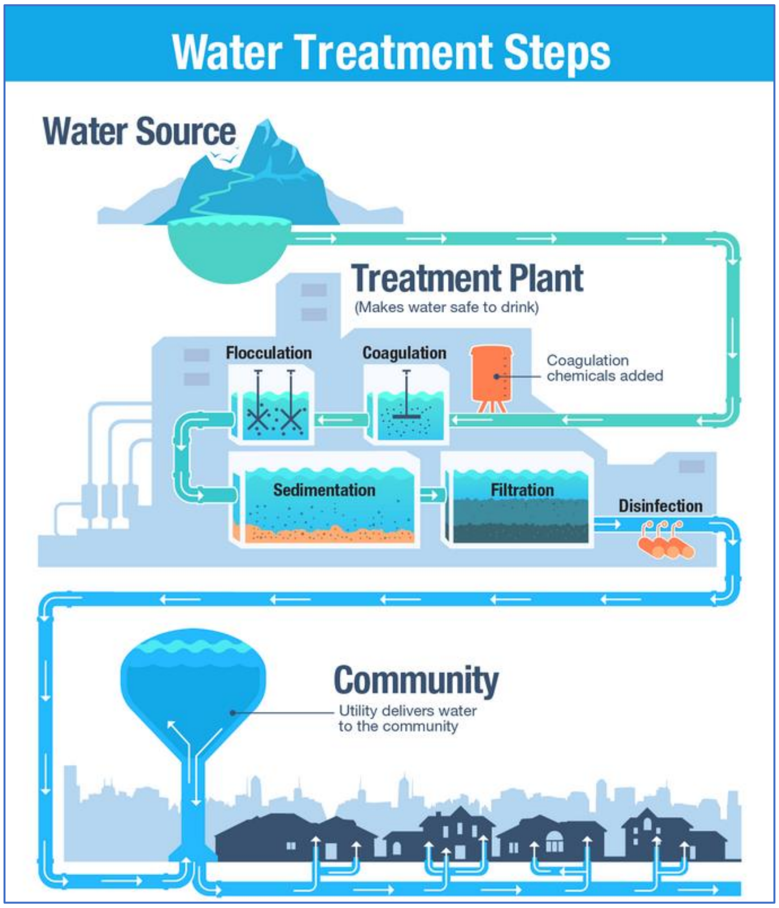


Figure 6: Water Treatment Steps
Source: Centers for Disease Control and Prevention (CDC)[61]

The Spanish Fork Wastewater Treatment Plant in Utah is currently in the process of updating their plant, in part to meet new water quality standards. In anticipation of the new plant which will begin operation in 2025,[62] they have released a video that explains the current plant's treatment process which starts right as wastewater reaches them. The water then undergoes a rigorous treatment process. These details can be explored by accessing the following video which is linked below.

Follow this link to access video

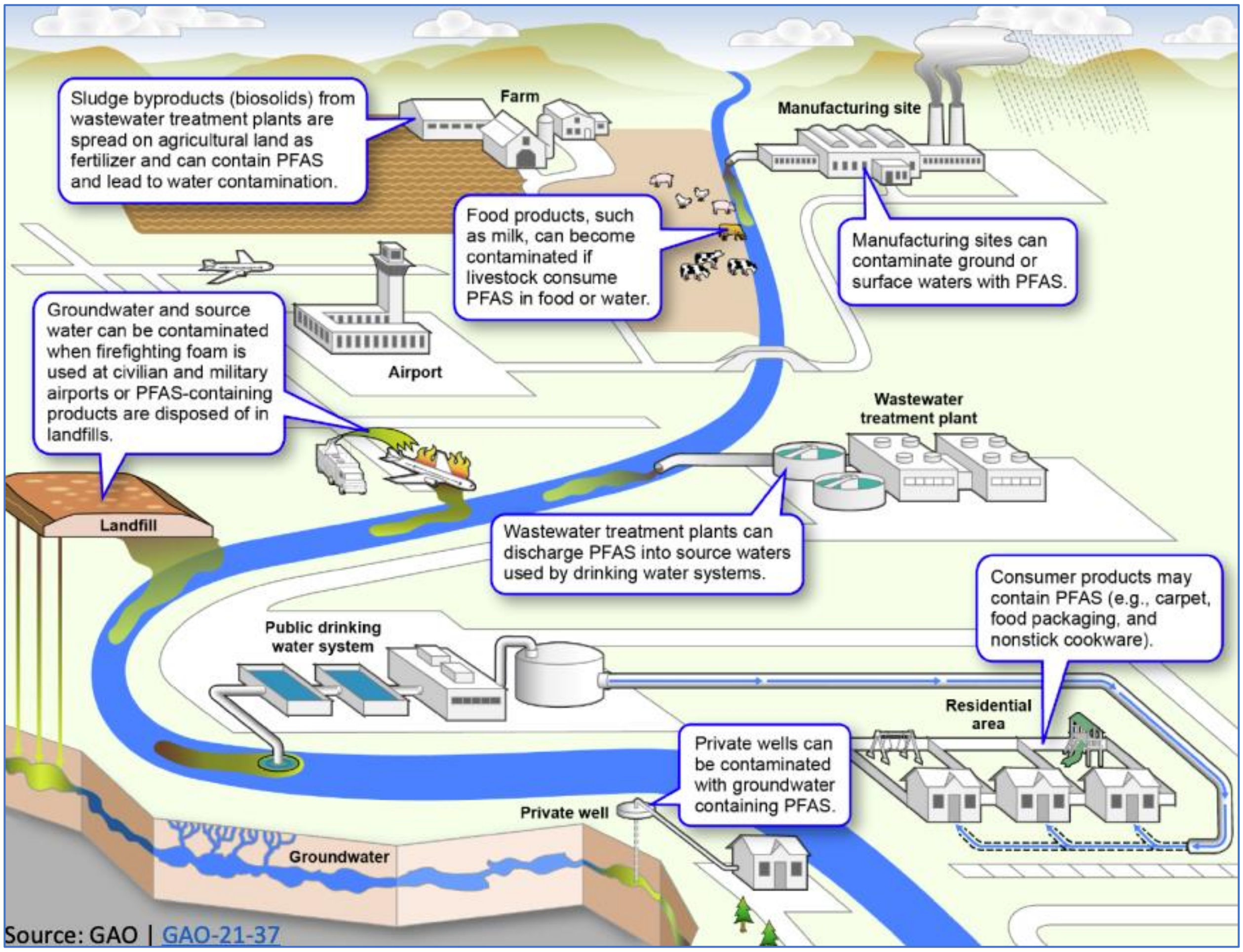
Figure 7: Wastewater Treatment Plant: From Beginning to End

Source: Spanish Fork 17[63]

2.2. Wastewater and PFAS

According to the EPA, there is insufficient data regarding the control and source of PFAS entry in wastewater treatment plants. There is ongoing research on pre-treatment and treatment technologies that remove PFAS in sources of high concentration (such as textile manufacturing facilities) to mitigate PFAS concentration in downstream treatment and disposal activities. The EPA is working toward identifying the source of large PFAS contributions that feed into wastewater and biosolids, so that pre-treatment technologies and actions will lower PFAS concentrations before water travels to treatment facilities.[64]

The following figure, from an EPA presentation in early 2023, illustrates sources of PFAS in the environment. Wastewater treatment plants are one of the sources of PFAS circulation, either by releasing PFAS into source water or spreading PFAS-concentrated biosolids on agricultural land.[65]



Source: GAO | GAO-21-37

Figure 8: Sources of PFAS in the Environment
Source: U.S. Environmental Protection Agency (EPA)[66]

Wastewater treatment plants can also be responsible for releasing PFAS into the environment from air emissions and residual disposal.[67]

According to the EPA, the "fate of PFAS through wastewater treatment plants is not well characterized." PFAS exists in solid residuals (which are either incinerated, used in land applications, or end up in a landfill) and biosolids. In the case of wastewater treatment, pretreatment has a higher probability of removal success.[68]

According to the figure below, which is based on the 2021 Biosolids Annual Program Reports gathered by the EPA, 43% of biosolids went to land application, 42% went toward landfilling, and 14% were incinerated.[69]

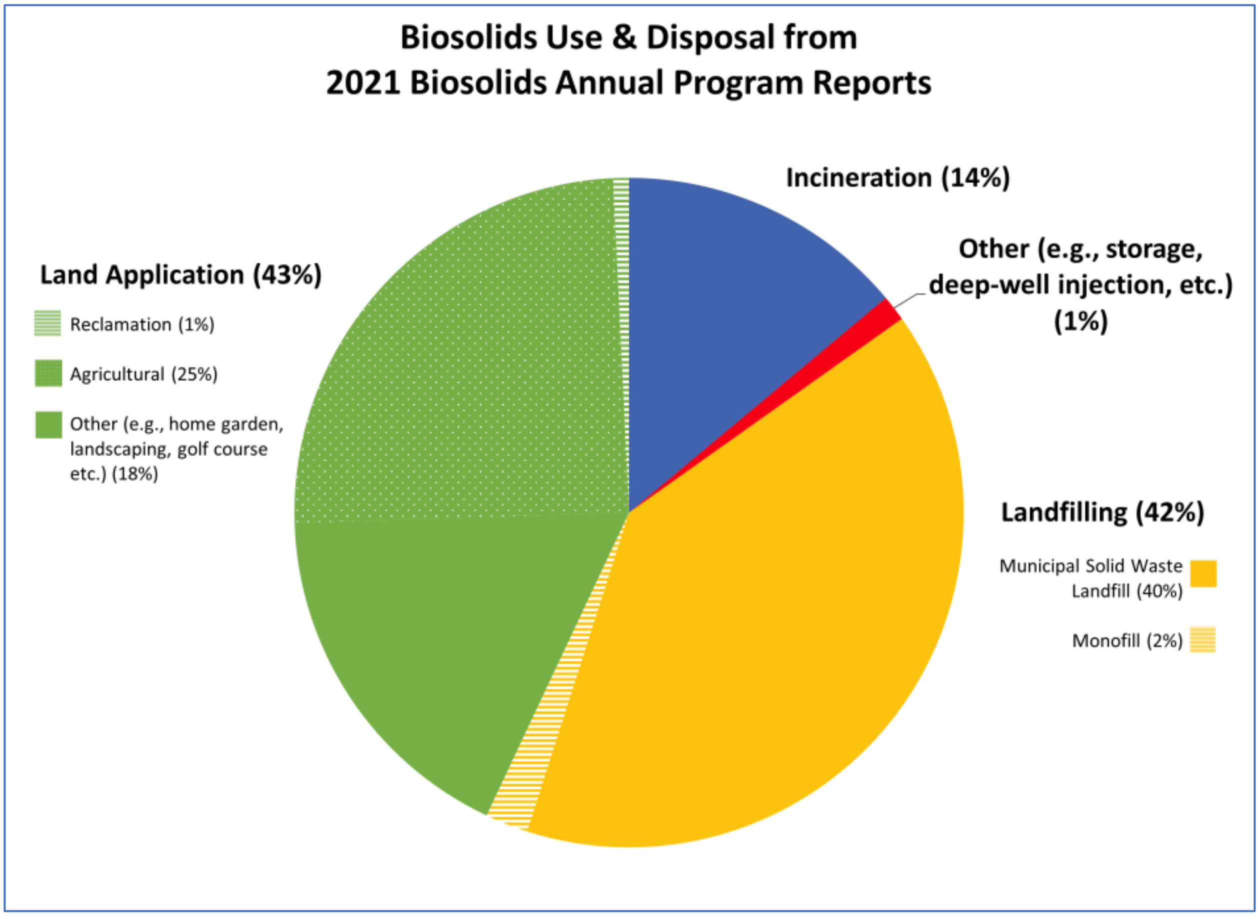


Figure 9: Biosolids Use & Disposal from *2021 Biosolids Annual Program Records*
Source: U.S. Environmental Protection Agency (EPA)[70]

2.3. Challenge of PFAS Resulting from WWTP

Concern for the consequences of biosolid use in land applications is a growing issue which has spurred potential biosolid land use prohibition. One danger of using biosolids in land applications is the possibility that PFAS could release into groundwater through soil after it is used in land applications.[71] The EPA has noted a deficiency in information related to “the fate of PFAS in land applied biosolids and other PFAS-containing land applied residuals” and “the transport of PFAS in the subsurface.”[72] The EPA does not have any regulations or standards for the concentration levels of PFAS in land application.[73]

Several states are considering the dangers of PFAS in land applications, whether it is implementing their own regulations, or conducting research. For example, in Michigan, the Land Application Workgroup created by the Michigan PFAS Response Team (MPART) is working in conjunction with EGLE's Industrial Pretreatment Program (IPP) staff is in the midst of exploring the ways PFAS in wastewater treatment plant biosolids and influent and effluent water are related as well as how the land applied materials could impact groundwater, soil, and surface water.[74]

In Wisconsin, the Wisconsin Department of Natural Resources' has an objective to eliminate the use of municipal biosolids that contain industrial PFAS compounds. Their intended protocol is for wastewater treatment facilities to identify and reduce PFAS concentrations for biosolids. This process will involve biosolid sampling, in turn, indicating any need to potentially find the sources contributing to the high PFAS concentration so that reduction strategies can be implemented.[75]

According to the EPA's PFAS Strategic Roadmap, the EPA is working on lowering the upstream discharge of PFAS by releasing guidance for states to utilize the National Pollutant Discharge Elimination System permits and pretreatment programs that will allow for additional monitoring for PFAS discharge. It's intended to mitigate the discharge of PFAS at its source, as well as gather information, and provide means for states to connect with the community to take measures at these sites. There is also a forthcoming release for a full PFOA and PFAS risk assessment in biosolids that will be available in 2024.[76]

3.0 Current WWTP Methods of PFAS Containment & Assessment of the Problem

There are roughly 4,200 major WWTP facilities and 10,900 minor ones in the U.S., according to the EPA's Facility Registry Service and Integrated Compliance Information System data.[77] (Major WWTPs can typically process 1 million gallons per day or more.)[78, 79] Only 75 or so are privately owned; the rest of the 15,100 total are publicly owned water treatment plants or POTWs, as termed by the Clean Water Act.[80] The distribution of WWTPs over the continental U.S. is shown in the following figure.

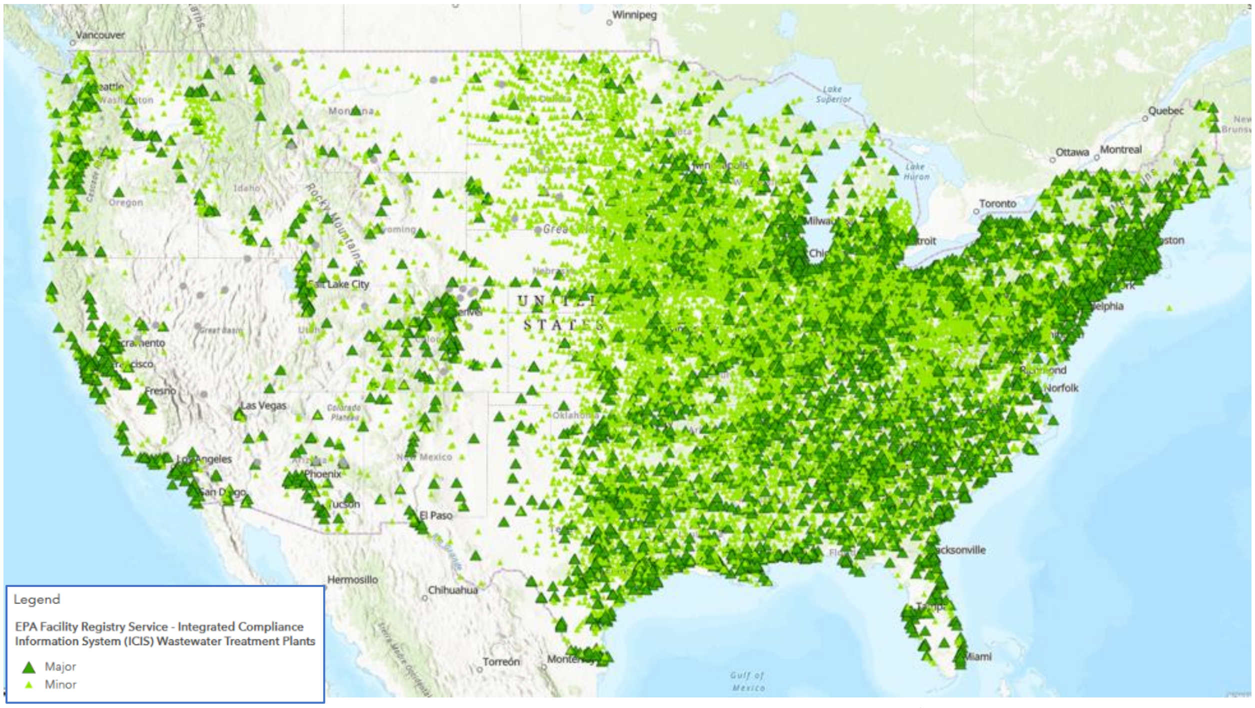


Figure 10: Wastewater Treatment Plant Locations, Compiled from the EPA Facility Registry Service and Integrated Compliance Information System (June 2023)

Source: EPA, Shared Enterprise Geodata and Services[81]

Only a handful of PFAS remediation technologies for water have been field-demonstrated at scale and have been well-documented in practice and through peer-reviewed research. For liquids, they include granular activated carbon (GAC), ion exchange resins (IX), and high-pressure membranes, namely, reverse osmosis (RO) and nanofiltration (NF). Residuals from these processes are typically disposed of in landfills or destroyed through incineration.[82] Further information about PFAS removal technologies is available from ERG's 2021 *Evaluation of Industrial Wastewater PFAS Treatment Technologies Report*, prepared for the EPA. The EPA's 2021 *Multi-Industry Per- and Polyfluoroalkyl Substances (PFAS) Study – 2021 Preliminary Report* describes wastewater characteristics by industry.

In what follows, the four predominant treatment strategies and two disposal/destruction methods are discussed first, followed by a broader discussion of WWTP operators' concerns about PFAS contamination and stepped-up requirements for the removal and destruction of PFAS in wastewater.

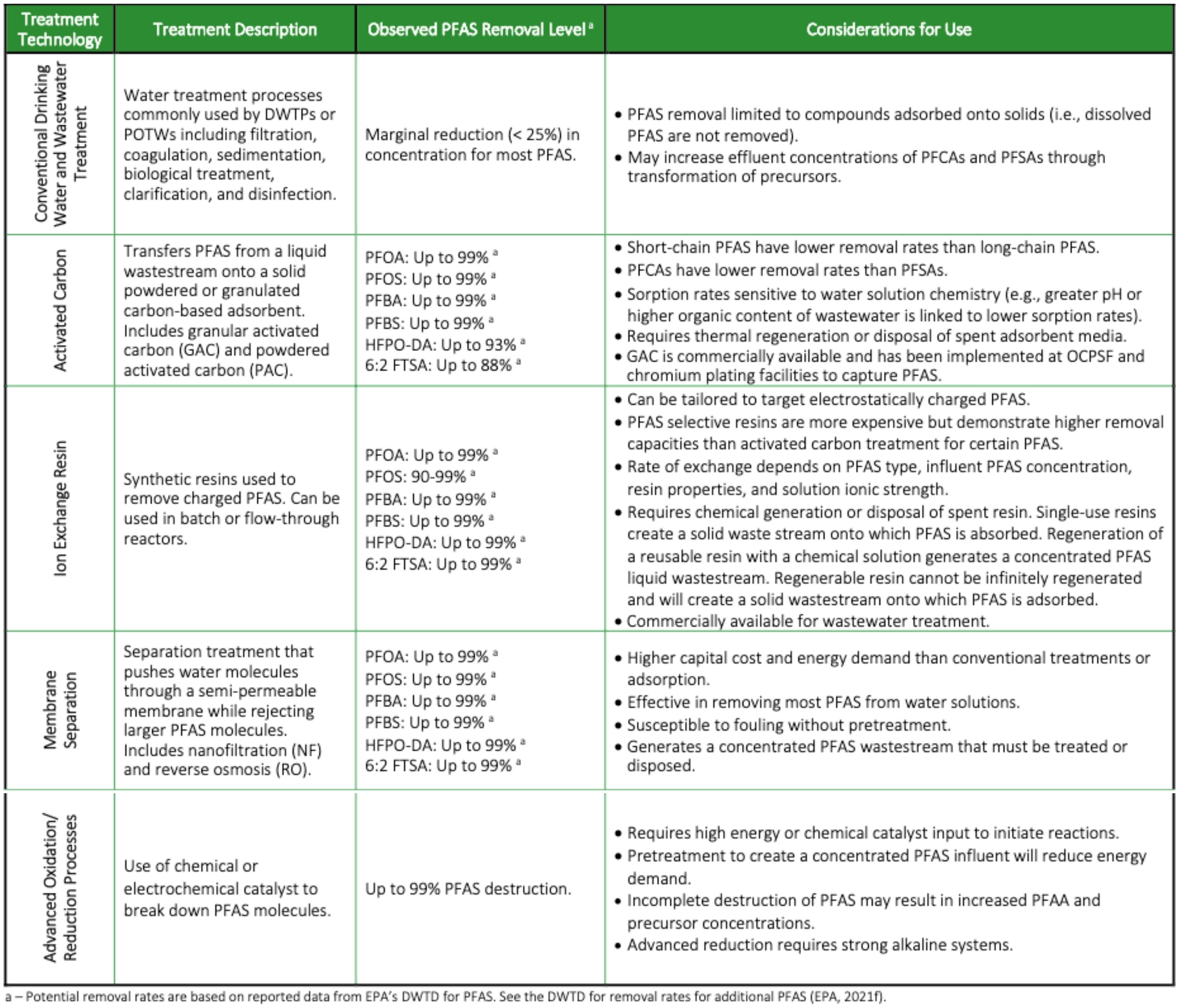
3.1. Removal Methods for Wastewater

Elevated levels of PFAS are commonly found in wastewater treatment plant (WWTP) influents.[83] Some PFAS—primarily long-chain compounds—may be removed to a very limited extent by more standard treatment processes (generally >5%–25%) not targeted at PFAS,[84, 85, 86] but the PFAS removal that does take place is primarily limited to adsorption onto solids.[87] Powdered activated carbon (PAC) in particular can be moderately effective at removing long-chain PFAS (>80%) but is less effective with short-chain PFAS (<40%).[88, 89] Unlike granular activated carbon (discussed below), PAC cannot be regenerated and must be landfilled or destroyed when spent.[90] Aside from PAC, conventional wastewater treatment methods generally do not degrade carbon-fluoride bonds at all, and so they have little or no effect on PFAS loads.[91] Advanced treatment technologies that do target PFAS, however, are not typically used due to increased costs.[92]

The PFAS remediation technologies that are most widely used and generally considered most effective for removing PFAS from water are **granular activated carbon (GAC)**, **ion exchange resins (IX)**, **reverse osmosis (RO),** and **nanofiltration (NF)**.[93, 94, 95, 96, 97, 98] These are the liquid treatment technologies designated by the ITRC (Interstate Technology and Regulatory Council) as field-implemented—successfully demonstrated at full-scale across multiple sites by multiple operators.[99] The granular activated carbon (GAC) and ion exchange resin (IX) methods are both sorption technologies, whereas reverse osmosis (RO) and nanofiltration (NF) are membrane separation technologies. Pretreatment is required for any of these technologies to effectively remove PFAS from wastewater.[100, 101, 102]

The table below is from the EPA's 2021 *Multi-Industry Per- and Polyfluoroalkyl Substances (PFAS) Study – 2021 Preliminary Report*. It summarizes common PFAS removal technologies.

Table 2: Available PFAS Treatment Technologies



Treatment Technology	Treatment Description	Observed PFAS Removal Level [a]	Considerations for Use
Conventional Drinking Water and Wastewater Treatment	Water treatment processes commonly used by DWTPs or POTWs including filtration, coagulation, sedimentation, biological treatment, clarification, and disinfection.	Marginal reduction (< 25%) in concentration for most PFAS.	• PFAS removal limited to compounds adsorbed onto solids (i.e., dissolved PFAS are not removed). • May increase effluent concentrations of PFCAs and PFSAs through transformation of precursors.
Activated Carbon	Transfers PFAS from a liquid wastestream onto a solid powdered or granulated carbon-based adsorbent. Includes granular activated carbon (GAC) and powdered activated carbon (PAC).	PFOA: Up to 99% [a] PFOS: Up to 99% [a] PFBA: Up to 99% [a] PFBS: Up to 99% [a] HFPO-DA: Up to 93% [a] 6:2 FTSA: Up to 88% [a]	• Short-chain PFAS have lower removal rates than long-chain PFAS. • PFCAs have lower removal rates than PFSAs. • Sorption rates sensitive to water solution chemistry (e.g., greater pH or higher organic content of wastewater is linked to lower sorption rates). • Requires thermal regeneration or disposal of spent adsorbent media. • GAC is commercially available and has been implemented at OCPSF and chromium plating facilities to capture PFAS.
Ion Exchange Resin	Synthetic resins used to remove charged PFAS. Can be used in batch or flow-through reactors.	PFOA: Up to 99% [a] PFOS: 90-99% [a] PFBA: Up to 99% [a] PFBS: Up to 99% [a] HFPO-DA: Up to 99% [a] 6:2 FTSA: Up to 99% [a]	• Can be tailored to target electrostatically charged PFAS. • PFAS selective resins are more expensive but demonstrate higher removal capacities than activated carbon treatment for certain PFAS. • Rate of exchange depends on PFAS type, influent PFAS concentration, resin properties, and solution ionic strength. • Requires chemical generation or disposal of spent resin. Single-use resins create a solid waste stream onto which PFAS is absorbed. Regeneration of a reusable resin with a chemical solution generates a concentrated PFAS liquid wastestream. Regenerable resin cannot be infinitely regenerated and will create a solid wastestream onto which PFAS is adsorbed. • Commercially available for wastewater treatment.
Membrane Separation	Separation treatment that pushes water molecules through a semi-permeable membrane while rejecting larger PFAS molecules. Includes nanofiltration (NF) and reverse osmosis (RO).	PFOA: Up to 99% [a] PFOS: Up to 99% [a] PFBA: Up to 99% [a] PFBS: Up to 99% [a] HFPO-DA: Up to 99% [a] 6:2 FTSA: Up to 99% [a]	• Higher capital cost and energy demand than conventional treatments or adsorption. • Effective in removing most PFAS from water solutions. • Susceptible to fouling without pretreatment. • Generates a concentrated PFAS wastestream that must be treated or disposed.
Advanced Oxidation/ Reduction Processes	Use of chemical or electrochemical catalyst to break down PFAS molecules.	Up to 99% PFAS destruction.	• Requires high energy or chemical catalyst input to initiate reactions. • Pretreatment to create a concentrated PFAS influent will reduce energy demand. • Incomplete destruction of PFAS may result in increased PFAA and precursor concentrations. • Advanced reduction requires strong alkaline systems.

a – Potential removal rates are based on reported data from EPA's DWTD for PFAS. See the DWTD for removal rates for additional PFAS (EPA, 2021f).

Source: EPA (September 2019)[103]

Each treatment method produces residuals that require disposal or further treatment, typically handled through landfilling or incineration, which are discussed in the next section.

Granulated Activated Carbon (GAC)

The most established and widely deployed technology for PFAS removal from water is GAC. GAC has been used in drinking water and wastewater treatment to manage other contaminants for decades, and in the U.S., the technology has been applied to municipal drinking water and wastewater treatment for decades.[104] While an overall estimate of the number of wastewater or drinking water plants treating with GAC was not available, the EPA identified 34 full-scale drinking water treatment plants in the literature using GAC.[105]

EPA identified 34 full-scale drinking water treatment plants in the literature that use Granulate Activated Carbon (GAC).

GAC itself is a porous adsorption media made from materials such as bituminous coal, lignite coal, or coconut shells, with very high internal surface area.[106, 107, 108] Bituminous coal seems to be the most effective at PFAS removal, based on available research.[109] Following the necessary pretreatment,[110] the GAC treatment process is as follows, in the words of the EPA:

> “When water is treated with GAC, it passes through treatment columns or beds containing GAC. The process separates dissolved contaminants from the water through adsorption to the surfaces in the pores of the GAC.”[111]

Elsewhere, a recent EPA report goes on to state that GAC treatment removes PFAS “primarily through hydrophobic partitioning of the fluorinated tails or electrostatic interactions from the anionic functional group.”[112] Breakthrough refers to the point at which the GAC’s ability to adsorb additional molecules has been significantly reduced.[113]

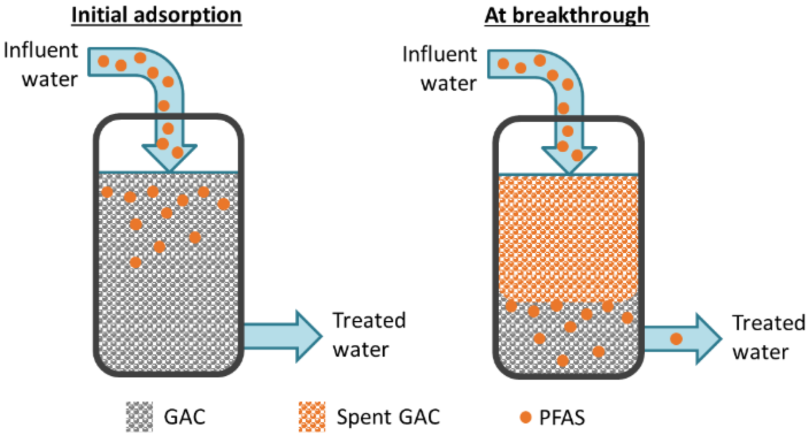


Figure 11: Granular Activated Carbon Treatment Process
Source: EPA (February 2023)[114]

GAC is usually performed ex situ by pumping water through the treatment system; GAC treatment may follow the conventional filtration process.[115, 116, 117] Pumping and treatment with GAC has been proven effective for removing long-chain PFAS from contaminated water. GAC removal capacity for individual PFAS chemicals, however, varies, and adjustments would be required for effective removal of short-chain PFAS.[118] The contact time required for PFAS removal is typically 10-20 minutes.[119, 120]

In the short video linked below, the City of Scottsdale's Water Department briefly illustrates treatment with GAC.

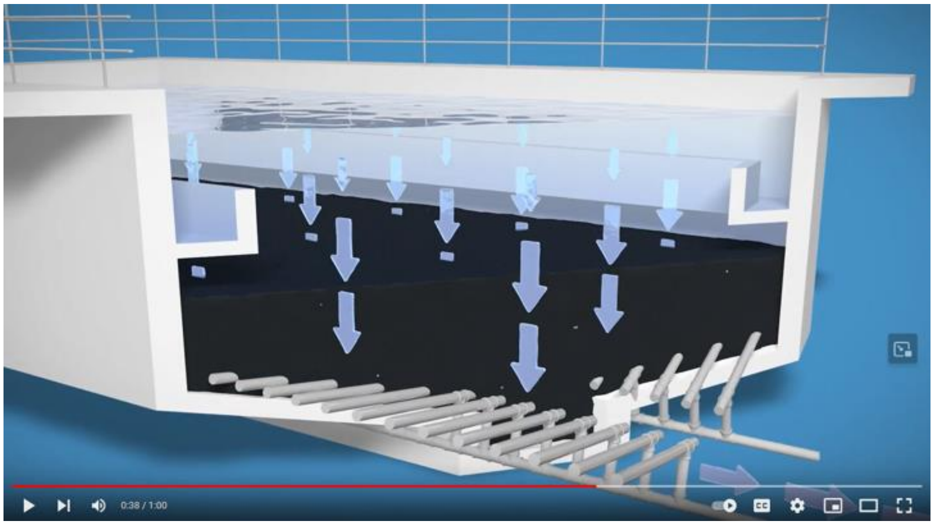


Figure 12: Granular Activated Carbon Treatment Within a Facility
Source: Scottsdale Water via YouTube (September 2019)[121]

Spent GAC contains PFAS, so disposal remains a concern when the GAC reaches the end of its useful life.[122, 123] At that point, it is often reactivated, that is, submitted to a high-temperature thermal treatment using a multiple hearth furnace or rotary kiln, for instance, to volatilize and destroy adsorbed contaminants, so that the GAC can be reused.[124] Fully spent GAC requires destruction or disposal, generally through incineration or landfilling.[125]

Ion Exchange Resin (IX)

The second most common method of PFAS removal is treatment with ion exchange resin (IX).[126] As with GAC, IX has been used for decades in other water treatment applications for water softening, demineralization, and removal of contaminants such as arsenic.[127, 128, 129] While the use of selective IX resins to contain PFAS is a newer method, its high removal effectiveness is relatively well documented.[130] Again, as with GAC, an overall estimate of the number of wastewater or drinking water plants treating with IX was not found, the EPA identified 7 drinking water treatment plants that have implemented IX at full scale, the first of which became operational in 2017.[131] The largest IX system for removing PFAS from water is in Yorba Linda, CA and is used to treat potable water from local wells.[132]

EPA identified 7 drinking water treatment plants that have implemented **Ion Exchange Resin (IX)** at full scale, the first of which became operational in 2017.

Water must undergo pretreatment for IX resin treatment to be effective and for the resin to maintain its efficacy.[133, 134] In ion exchange resin treatment, water passes through a bed of selective ion exchange resins, which remove PFAS through ion exchange and adsorption using the "head" and "tail" of the PFAS compound (see depiction of PFOS and PFOA in the introduction).[135] A 2021 EPA report describes the IX treatment process in the following way,

> "IX uses synthetic resins to remove charged contaminant ions using exchange sites on the resin beads. The charged resin sites attract oppositely charged contaminant ions. Anion resins are positively charged and attract negatively charged contaminant ions and cation resins are negatively charged to attract positively charged contaminant ions. PFAS compounds can be either positively or negatively charged due to variation in functional groups so ion exchange resins must be selected for groups of PFAS compounds rather than all PFAS compounds. Since PFCAs [e.g., PFOA] and PFSAs [e.g., PFOS] typically contain an anionic charge, they may be removed by anion exchange resins."[136]

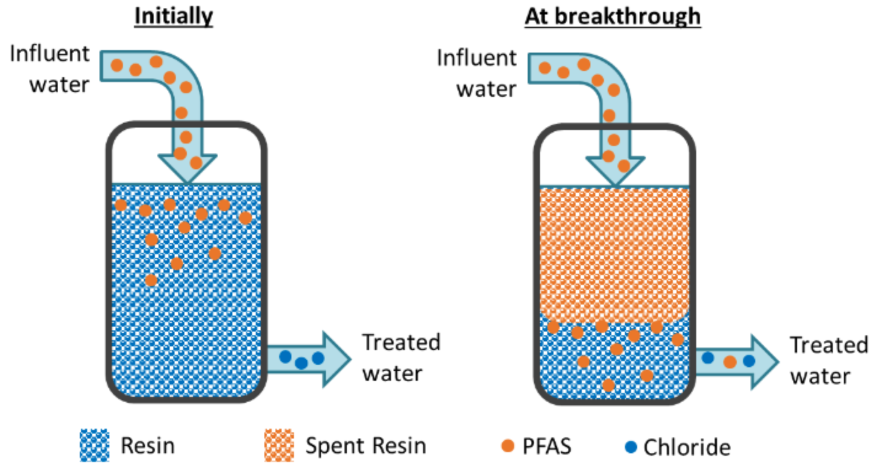


Figure 13: Ion Exchange Treatment Process

Source: EPA (February 2023)[137]

Single-use resins (best suited for low concentrations of PFAS) or regenerable resins (best suited to high levels of PFAS contamination) may be used. Although they are not yet widely used, regenerable resins also present advantages in that they can be made to regain their exchange capacity using a regenerant solution onsite.[138]

The contact time required for PFAS removal is relatively short—1.5 – 5 minutes.[139] Configuration of the IX treatment unit is similar to GAC's, but the IX resin system typically takes up less than GAC and other systems.[140] Spent resin becomes loaded with PFAS and require disposal, usually landfilling or incineration. [141] Use of regenerable resin also produces PFAS-contaminated solvent and salt brine, which are used to flush the spent resin. While the solvent can be recycled, the distilled brine is treated with GAC and transferred to high-capacity IX media for incineration.[142] Compared to GAC, IX is generally more effective at PFAS removal but is more expensive by media weight.[143] IX treatment's cost effectiveness compared to GAC, however, depends on a site's specific characteristics (water chemistry, disposal costs, etc.).[144]

Reverse Osmosis (RO) and Nanofiltration (NF)

Reverse Osmosis (RO) and nanofiltration (NF), also established approaches for PFAS remediation, are membrane separation methods that remove contaminants from water by applying pressure to repeatedly move the water through a semipermeable membrane.[145, 146, 147] They are distinguished by the amount of pressure applied; RO typically uses higher pressure.[148] Pretreatment is required for both RO and NF to remove PFAS effectively. [149]

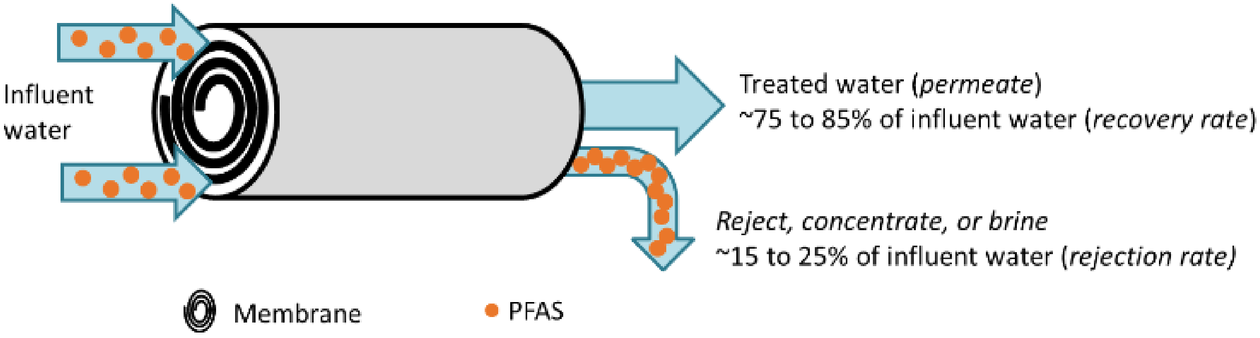


Figure 14: Reverse Osmosis/Nanofiltration Treatment Process
Source: EPA [150]

The membranes used are typically spiral-wound, with the layers of membrane material wrapped around a tube, pictured in the following figure.[151, 152]

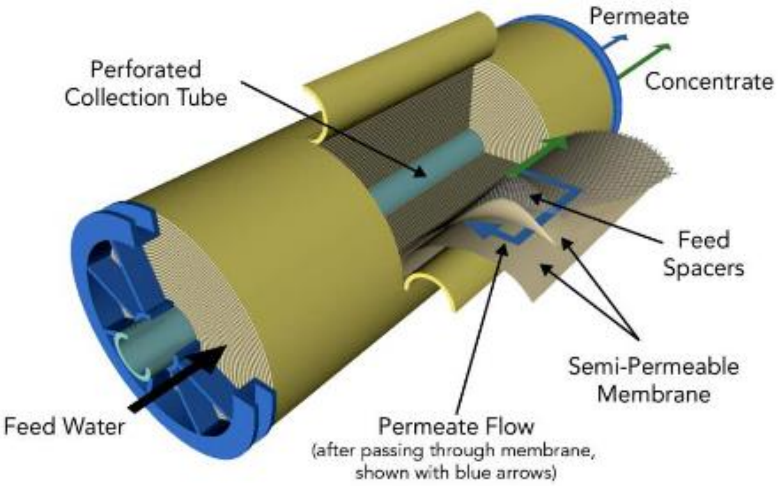


Figure 15: Spiral Wound Membrane for Reverse Osmosis Water Treatment
Source: DOE[153]

RO and NF are commonly used to remove a broad range of contaminants such as VOCs from drinking water, by industry to remove chemicals from water, and in desalination. Through bench studies and pilot projects, RO and NF have been demonstrated to be highly effective for removing a range of PFAS but tend to be most effective with lower flow rates, such as residential points of use. Differences in membranes affect the results of RO and NF, as some have been shown to filter out short-chain PFAS much less effectively. Pretreatment of wastewater may be crucial, as the membranes' capacity is easily compromised by the accumulation of materials like suspended solids that are difficult to remove from the membrane material. Cleaning solutions are required to maintain the membrane. RO and NF are a high energy and relatively expensive method, although pretreatment may help contain costs. The resulting PFAS-contaminated concentrate rejected by the membrane accounts for about 1/10 – 1/4 of the total water flow. It also requires additional treatment, permitted discharge, or disposal.[154, 155]

PFAS Removal Methods with Limited Implementation

Limited application PFAS removal technologies—using the Interstate Technology and Regulatory Council (ITRC)'s categorization—refers to PFAS removal technologies that have been implemented on a very limited number of sites worldwide, on a small scale, and/or by a small number of practitioners and may need additional scholarly research to confirm their efficacy.[156] PFAS removal technologies of this sort include:

- Advanced oxidation processes (e.g., chemical oxidation, electrochemical oxidation)
- Colloidal activated carbon
- Foam fractionation
- Deep well injection[157]
- Electrocoagulation.[158, 159]

These and more emerging technologies are discussed in section 5.0 below.

Overall, given current practices and accessible technologies, treatment trains or the combination of multiple remediation processes is likely to be the most effective approach, combining the strengths of each approach while avoiding the worst of their limitations.[160] Current PFAS remediation approaches have generally proven inadequate at PFAS removal let alone destruction, as recent studies indicate that the total PFAS loads are higher in treated leaving WWTPs than in raw influent entering WWTPs,[161, 162, 163] likely as a result of wastewater treatment processing breaking more complex compounds into terminal PFAS.[164, 165]

3.2. PFAS Disposal/Destruction Methods for Wastewater

Residuals from GAC, IX, and RO/NF treatment are typically disposed of through **landfilling**, which may result in PFAS leaching, or destroyed through **incineration**, which mineralizes PFAS using very high temperatures (above 1,100 degrees C).[166]

The residuals from GAC, IX, and RO/NF are disposed of (but not destroyed) through landfilling and incineration.

Landfilling

Landfilling, of course, is not a destruction method for PFAS-containing solids. It is a method of removing the contaminated material from the treatment location to a controlled facility in order to limit further risk of contamination. This has the undesirable effect of "transferring potential liability to another location," as ITRC puts it. PFAS is considered a non-hazardous material in most states for landfill permitting, but an increasing number of landfills will no longer accept soil and other solids contaminated with PFAS. [167]

Landfilling also presents the risk of PFAS-contaminated leachate. In a study of 200 landfills testing in September 2021, the EPA found that 95% of leachate contained some mix of 63 different PFAS. As a result, the EPA's Effluent Guidelines Program Plan 15, released in November 2022, announced the EPA's intention to update the landfill standards category to include limits of PFAS levels.[168, 169] The EPA "estimates that approximately 13,200,000 individuals live within one mile of a landfill," and that "in these communities, the average median income is $48,100 and on average 31 percent of the population belongs to a minority group."[170]

In a study of 200 landfills testing in September 2021, the EPA found that 95% of leachate contained some mix of 63 different PFAS.

Incineration

As defined by ITRC, incineration is,

> "[A] Destruction (mineralization) of chemicals using heat. Heat is applied directly to the PFAS- contaminated solids (soil/sediment/spent adsorbents/waste) or liquids (water/wastewater/leachate/chemicals). Vaporized combustion products can be further oxidized and/or captured (precipitation, wet scrubbing) and/or further oxidized at elevated temperature."[171]

Incineration is a standard method for handling solid and liquid wastes and the only potential means of destroying PFAS that is well-established.[172, 173] It is commonly applied to PFAS-contaminated, solid residuals, such as spent GAC, sludge, or biosolids.[174] The process, however, is very energy-intensive and therefore expensive, and a limited number of facilities are permitted to incinerate PFAS-contaminated solids, constrained by federal, state, and municipal regulations for waste incineration.[175]

The EPA and other authorities question whether there is sufficient data to determine whether this method fully mineralizes PFAS or transfers some PFAS to atmospheric emissions.

Moreover, the EPA and other authorities question whether there is sufficient data to determine the extent to which incineration destroys various PFAS and to which extent it may release other PFAS compounds into the air. The emissions from PFAS incineration are not well understood and are a topic of continuing research.[176, 177] Some studies indicate that incomplete destruction via incineration can result in the formation of other PFAS compounds in the emissions.[178] In the event that incineration completely destroys PFAS, the resulting substances may include carbon monoxide, carbon dioxide, water, hydrogen fluoride, and sulfur molecules or sulphuric acid—some of which may become problematic in their own right.[179] Efforts to develop more effective and less costly destruction processes are ongoing.

Emerging PFAS Destruction Methods

Sources documenting other thermal treatment methods under investigation (e.g., pyrolysis, gasification, hydrothermal processing) are being collected in the EPA's PFAS Thermal Treatment Database.[180] Another emerging method of PFAS destruction under investigation is sonochemical oxidation/ultrasound, whereby "PFAS are thermally destroyed and hydroxyl radicals are generated for destruction of co-contaminants." [181] The method has thus far been demonstrated in bench studies and a pilot study for aqueous film-forming foam (AFFF).[182] The technology is discussed further in section 5.0.

An emerging method of PFAS destruction under investigation is sonochemical oxidation/ultrasound.

3.3. Wastewater Treatment Facilities' Perception of the Problem

WWTPs receive PFAS-contaminated stormwater and domestic, commercial, and industrial wastewater. Managing PFAS at the source, before they enter WWTPs, through industrial pretreatment programs (IPPs) and other measures is the most efficient way to control the levels of PFAS in WWTP discharge, but source reduction is by and large outside of WWTPs' control.[183, 184] Several themes emerge from the statements made over the last five years by organizations that represent water utility and wastewater treatment professionals, such as the AWWA (American Water Works Association), Association of Metropolitan Water Agencies (AMWA), National Association of Clean Water Agencies (NACWA), National Association of Water Companies (NAWC), Water Environment Federation (WEF). From at least 2018-2019 on, these groups have generally acknowledged the widespread presence of PFAS in water systems, recognized emerging evidence of health and environmental risks of contamination and the need for a more robust body of research, and, in a broad sense, supported the EPA in establishing further restrictions targeted at PFAS mitigation.[185]

Concerns over controlling PFAS contamination, of course, persist. The National Association of Clean Water Agencies (NACWA), AWWA (American Water Works Association), and Association of Metropolitan Water Agencies (AMWA) each submitted comments in response to the Office of Science and Technology Policy (OSTP)'s RFI, Identifying Critical Data Gaps and Needs To Inform Federal Strategic Plan for PFAS Research and Development, released in July 2022. The AWWA is an organization whose membership represents about 80% of drinking water utilities and about 50% of wastewater treatment systems.[186] In the association's 2023 *State of the Water Industry* survey,[187] respondents were asked to rate how concerned they were about compliance with current and future regulations regarding a list of about 15 contaminant categories. PFAS/PFOAs (in connection with health advisories) was ranked number one. 20% of respondents reported they were "extremely concerned" about PFAS—the highest rating on a five-point scale.[188]

Three major concerns these groups have expressed about managing PFAS are:

- Uncertainty about the Effluent Limitation Guidelines (ELGs) and approved analytical methods for PFAS to be set by EPA
- How the upgrades needed to effectively remove and destroy PFAS will be funded
- What liability protections will be in place for water utilities and WWTPs as recipients of PFAS-contaminated wastewater.

Uncertainty About Effluent Limitation Guidelines and Approved Testing Methods

The EPA has not yet proposed PFAS effluent limitations guidelines and pretreatment standards (ELGs) for wastewater treatment and most industry dischargers.

The targets for PFAS levels in discharged wastewater are uncertain, as the EPA has not yet proposed PFAS effluent limitations guidelines and pretreatment standards (ELGs) for wastewater treatment and most industry dischargers under the National Pollutant Discharge Elimination System (NPDES) permitting program. In its 2021 *PFAS Strategic Roadmap*, the EPA stated its intention to "make significant progress" on its work to address PFAS-contaminated effluent through ELGs by the end of 2024,[189] but a more specific timeline for a PFAS ELG proposal that directly applies to wastewater treatment plants has not been announced.

Organizations such as the National Association of Clean Water Agencies (NACWA)—though supportive of EPA's implementation of ELGs governing PFAS levels in principle—have expressed concern over the achievability of PFAS limits to be set by EPA. In May 2021, NACWA released a statement that read, in part,

> "NACWA supports ELGs and pretreatment standards as an effective way of controlling PFAS at its sources. Since there are currently no cost-effective techniques available to treat PFAS in the volumes of wastewater managed by clean water utilities, controlling PFAS at the source is the most viable option.
>
> NACWA requested [from EPA] that any ELGs and pretreatment standards developed for PFAS be as flexible as possible, to account for the new information and treatment technologies that are likely to emerge as research on PFAS continues. In addition, NACWA recommended that POTWs [publicly owned treatment works] not be made responsible for enforcing limits on PFAS that would be nearly impossible to enforce, such as a 'zero discharge' limitation."[190]

Relatedly, NACWA and others have expressed reservations about the sufficiency of PFAS analytical methods to support accurate monitoring and effective regulation at a reasonable cost. "One of the most challenging current aspects of the PFAS discussion," according to NACWA, "is that there are no uniform, approved testing methods or established risk thresholds," particularly for wastewater.[191]

While the EPA worked with the Department of Defense to develop Draft Method 1633 first and foremost to test for PFAS compounds in drinking water, EPA announced in September 2021 that Draft Method 1633 was its first lab-validated method to test for 40 PFAS in eight environmental media, including wastewater.[192] Nevertheless, as the EPA states, "Currently, there are no EPA-approved methods in 40 CFR Part 136 for analyzing PFAS" in drinking water, wastewater, or any other water type.[193] The fourth draft of Method 1633 was issued in July 2023, with the final draft expected before 2024.[194] Prior to Method 1633, modifications of other EPA analytical methods or in-house methods were used.[195] (See EPA's CWA Analytical Methods for Per- and Polyfluorinated Alkyl Substances [PFAS] or

EPA states, "Currently, there are no EPA-approved methods in 40 CFR Part 136 for analyzing PFAS" in drinking water, wastewater, or any other water type.

ECOS's *Processes and Considerations for Setting State PFAS Standards*, 2023 update, page 30 and following, for further information about testing methods.)

There are also concerns about the availability of labs adequately prepared to run the necessary PFAS tests and the relative cost of doing so from state agencies, as well as wastewater utilities. In comments submitted to the EPA in April 2023 regarding the proposed PFAS National Primary Drinking Water Regulation, the Water Environment Federation (WEF) succinctly stated that in the short term, "The demand for labs equipped to test PFAS will severely outweigh available lab capacity."[196] In March 2023 state environmental agency survey update, ECOS (the Environmental Council of the States) reported that among five states (ME, MN, NC, NY, WI) Draft Method 1633 turnaround times ranged from 14-45 days, and prices per water sample ranged from about $274 – $500. The respondent for New York's state agencies reported that Draft Method 1633 samples often cost twice what testing with the previously-used EPA Method 537.1 cost.[197]

How Will Upgrades Be Funded

Who will pay for the expensive upgrades or new equipment or facilities needed to effectively remove and destroy PFAS from wastewater is still unclear in the vast majority of cases. As stated in the introduction, the costs will be significant. The Minnesota Pollution Control Agency report issued in May 2023 estimates that retrofitting facilities and removing and destroying PFAS over a 20-year period will cost municipal wastewater treatment plants between $2.7 million and $18 million per pound of PFAS removed from effluent and $1.0 million to $2.7 million per pound of PFAS from biosolids, depending on facility size and the PFAS mix present.[198] The National Association of Clean Water Agencies (NACWA) expects individual utilities' operational costs to increase as much as 60% to meet anticipated PFAS regulations for wastewater.[199]

The question of how upgrades will be funded becomes all the more serious when considering the competing priorities WWTPs face, given the maintenance and repair needs of most systems' aging facilities.[200] In the same 2023 AWWA *State of the Water Industry* survey referenced above, when asked to rank 20 key issues facing the industry, respondents placed two issues related to major facilities maintenance and upgrades within the top three:

1. Rehabilitation & replacement (R&R) of aging water infrastructure
2. Long-term drinking water supply availability
3. Financing capital improvements.[201]

The organizations representing the drinking water and wastewater treatment sector have consistently pushed for the companies who have produced PFAS and used it in manufacturing other products to bear these costs. In a March 2023 press release, for instance, the National Association of Water Companies (NAWC), an organization representing "regulated water and wastewater companies, as well as those engaging in partnerships with municipal utilities,"[202] stated the following.

"Addressing the PFAS in the nation's water supply will cost billions of dollars."

> "Establishing a national standard for addressing these harmful ingredients from the nation's water supply provides clarity to all utilities, their customers and states while placing all water and wastewater systems in the same boat to navigate these uncharted waters.
>
> Make no mistake – addressing the PFAS in the nation's water supply will cost billions of dollars. It's a burden that under the current structure will disproportionately fall on water and wastewater customers in small communities and low-income families. Instead of coming from the pockets of water and wastewater customers and utilities, the polluters should be held directly responsible for the cleanup costs."[203]

The National Association of Clean Water Agencies (NACWA)'s stance on PFAS remediation funding reads, "NACWA's position is that the manufacturers of these chemicals should bear responsibility for the costs of clean up and treatment – a "polluter pays" model."[204] Another water organization, the National Rural Water Association (NRWA), won a $1.2 billion settlement in June 2023 from PFAS manufacturers, including DuPont, Chemours, and Corteva, to fund a Cost Recovery Program for utilities. Currently, that outcome is exceptional.[205]

PFAS Cleanup Liability

As the number of cases brought against companies who release PFAS into the environment through production and/or use increases,[206] concern among treatment facilities about potential liability resulting from the release of PFAS-contaminated effluent has also increased. The Association of Metropolitan Water Agencies (AMWA), for instance, expressed concern in their 2022 annual report over the EPA's proposed PFAS drinking water requirements in its "lack of liability protections given to drinking and wastewater utilities as passive receivers … [from] incurring cleanup liability related to PFAS removed from water supplies."[207]

As the Water Coalition Against PFAS, the five organizations (AWWA, AMWA, NACWA, NRWA, and WEF),[208, 209] are urging Congress to pass the Water Systems PFAS Liability Protection Act, which was referred to the Senate's Committee on Environment and Public Works in May 2023.[210] The bill would extend the "polluter pays" principle under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) to PFAS remediation and protect drinking water and wastewater systems from cleanup costs, provided that the treatment residuals were handled properly.[211, 212]

AWWA expressed concern over EPA's proposed PFAS drinking water requirements in its "lack of liability protections given to drinking and wastewater utilities as passive receivers … [from] incurring cleanup liability related to PFAS removed from water supplies."

4.0 State Initiatives & Regulations

4.1. Introduction

In the absence of finalized standards and regulations from the EPA governing acceptable PFAS levels in drinking water and the removal of PFAS from wastewater treated in wastewater treatment plants, it has largely been left up to states to determine how to address PFAS contamination in public water systems, rivers and streams, lakes, and so on. States' responses to the issues of PFAS in drinking water and wastewater, as well as the broader health and environmental risks of PFAS, have varied widely. In the absence of enforceable standards or recommended limits for PFAS levels in industrial and publicly owned treatment works (POTWs)'s wastewater discharges, a very limited number of states have put measures in place to control PFAS in wastewater.

For this reason and on account of the relationships between wastewater discharge, surface water, and source water for drinking water supplies, this section discusses state efforts to control PFAS in drinking water as well as wastewater. As the EPA has prioritized

The EPA has prioritized regulation of PFAS in drinking water before turning its attention to wastewater.

regulation of PFAS in drinking water[213] before turning its attention to wastewater and media, states at the forefront of controlling PFAS in drinking water ahead of the EPA are presumed most likely to take the lead in controlling PFAS in wastewater ahead of the EPA.

Before discussing states' regulatory trends (4.3), this section briefly introduces major producers and industrial users of PFAS chemicals (4.2). According to the EPA, there are “approximately 120,000 facilities subject to federal environmental programs [that] have operated or currently operate in industry sectors with processes that may involve handling and/or release of PFAS.”[214] The section continues by discussing states’ efforts to control PFAS contamination from so many facilities. After surveying overall trends in state regulation, guidance, legislation, and legal action governing PFAS in wastewater, biosolids, and drinking water (4.3), the section closes with closer examinations of the regulations and policies governing PFAS in wastewater and related media in three states: Minnesota (4.4), Oklahoma (4.5), and Louisiana (4.6).

4.2. Major Producers and Users of PFAS

Major manufacturers of legacy and emerging PFAS in the U.S. include **3M**, **Chemours** (formerly DuPont), **Arkema, Asahi, BASF Corporation, Clariant, Daikin, and Solvay Solexis**.[215, 216] These are also the eight companies that EPA enlisted, based on emission data, for its PFOA Stewardship Program (2006-2015) to meet voluntary PFOA manufacturing reduction targets.[217]

3M’s situation is illustrative. **3M**, based in Minneapolis, previously manufactured and presently manufactures a range of PFAS-containing products. Use of PFOS and PFOA have been phased out, and PFAS is no longer used in the flagship product Scotchguard. PFAS is used in some current 3M products, however, such as Novec aircraft cleaner and fluorinert electronic liquid (e.g., for use in semiconductor wafer fabrication and data center server immersion cooling). In December 2022, 3M announced plans to end PFAS manufacturing and use of PFAS in its products by 2025.[218, 219]

3M has faced thousands of lawsuits on account of PFAS since 2000.[220] 3M produced PFOA, PFOS, and other PFAS on the east side of Minneapolis and disposed of PFAS-contaminated waste in the area from the 1950s through the 1970s, contaminating drinking water and more. A lawsuit brought by the state against 3M for PFAS cleanup was settled in 2018 for $850 million.[221] Other major U.S. manufacturing sites with confirmed PFAS contamination are Cordova, IL and Decatur, AL.[222]

The major industries releasing PFAS into the environment identified and discussed in the EPA's 2021 *Multi-Industry Per- and Polyfluoroalkyl Substances (PFAS) Study* are in line with EPA's industry categorizations for the purpose of NPDES effluent permitting. They are:

- Organic Chemicals, Plastics and Synthetic Fibers (OCPSF)
- Metal finishing
- Pulp, paper, and paperboard
- Textiles mills
- Commercial airports.[223]

The study provides details on wastewater characteristics and regulatory requirements by industry. "Few facilities in these industries currently have monitoring requirements, effluent limitations, or pretreatment standards for PFAS in their wastewater discharge permits," EPA states in the report.[224]

A recent review article by Linda G. T. Gaines (2022) provides a detailed survey of the myriad historical and current applications from adhesives to the semiconductor industry. Patents were vital in identifying and tracking uses of PFAS, as "Unfortunately, like other chemicals, many PFAS are used in such a way that their use is a trade secret, or there is no requirement that their use be stated in a specific application."[225] While a few federal and state requirements have been instituted for selected consumer goods over the last year, the statement is still generally true. In a December 2021 statement, a group of concerned investors who manage $4.1 trillion worth of assets wrote to the world's 50 largest chemical companies, urging action and greater transparency around PFAS, in the interest of shareholders. "The chemical industry," the letter reads, "sits at the start of the supply chain so it has a role to play in driving the circular economy forward."[226]

A map is provided below to better illustrate the distribution of PFAS manufacturing and industrial use. The figure indicates the combined concentration of chemical production or manufacturing facilities that produce or use PFAS and facilities in industries likely to be using PFAS, per EPA records.[227, 228]

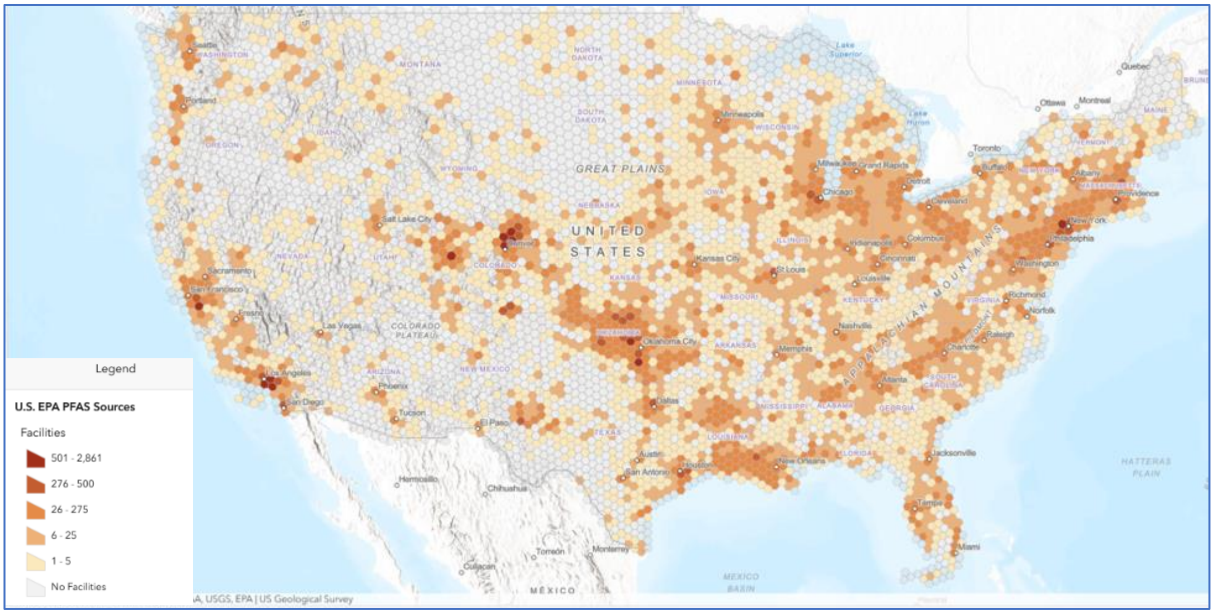


Figure 16: Density of PFAS Source Facilities Per 1,500 sq. km
Source: USGS, "PFAS in US Tapwater Interactive Dashboard"[229]

The highest concentrations of confirmed or presumed PFAS manufacturing or handling facilities appear to be in Southern California and San Jose, CA; Denver and Grand Junction, CO; the New York Metro area; and throughout Oklahoma; among other locations.

4.3. State Trends in PFAS Water Contamination Control

As mentioned in earlier sections, virtually all PFAS control in media other than drinking water has been left to the States thus far. Due to the persistence of PFAS chemicals, current and historical emissions cumulatively affect local areas, states, and regions.

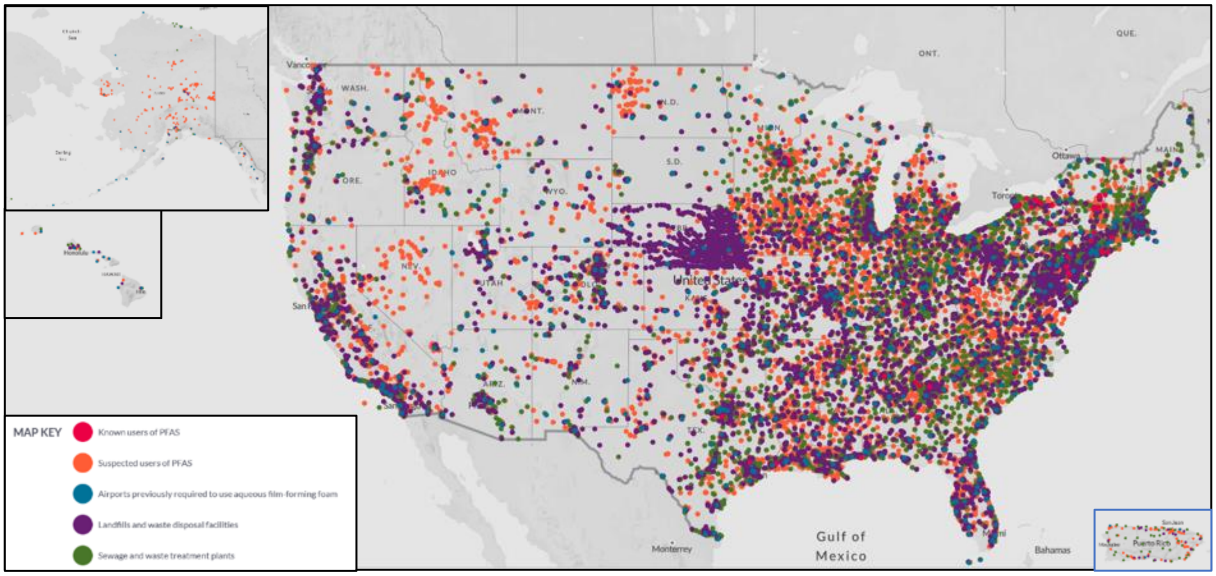


Figure 17: Known and Suspected Industrial, Landfill, and Wastewater Treatment Dischargers of PFAS, 2021
Source: Environmental Working Group (EWG)[230]

Areas with the greatest number of confirmed contamination sites or highest PFAS levels, however, are not necessarily those that have put the most stringent municipal or state restrictions in place. 30 states have put at least one rule (promulgated or interim) or advisory[231] in place that goes beyond the 2016 PFOA and PFOS Lifetime Health Advisories for at least one PFAS as of June 2023, in at least one environmental medium (drinking water, source water, groundwater, wastewater, soil, etc.).[232]

Wastewater

Most states are authorized to administer their own National Pollutant Discharge Elimination System (NPDES) permitting programs, and while the EPA has stated its intention to establish effluent limitations guidelines and pretreatment standards (ELGs) for PFAS in wastewater effluent, it has yet to do so. Crucial data about PFAS in wastewater treatment influent is also planned but is yet to be collected.[233] As for state regulations, as the EPA states in its caveats on its PFAS data tools, under NPDES, "Less than half of states have required PFAS monitoring for at least one of their permittees, and fewer states have established PFAS effluent limits for permittees."[234] At least 30 states have not conducted PFAS monitoring of wastewater influent or effluent; those that have include [235]
effluent.

The state regulations and permitting requirements that were found are:

- **Minnesota:** required municipal WWTPs to regularly test for PFAS according to the state's current monitoring plan.[236, 237]
- **New Hampshire:** a state law adopted in 2022 allows WWTPs to require industrial dischargers to test for PFAS.[238]
- **Oregon:** initiation levels[239] for PFOA, PFOS, PFNA, PFHpA, PFOSA in municipal wastewater[240]

Biosolids

There has been more state activity on PFAS-contaminated biosolids. Maine is at the forefront of restrictions placed on biosolid disposal due to PFAS contamination and currently the only state to impose a ban on land application, which was passed in 2022. Few other states have adopted legislation to address PFAS in biosolids.[241] Minnesota, for example, adopted a law in 2021 that allocated funding for the development of solutions to mitigate PFAS in land-applied biosolids. A number of states such as Maryland, Massachusetts, Illinois, Iowa, and Oklahoma, are currently considering legislation aimed at controlling PFAS in sludge and/or biosolids. Ten or so states (e.g., Michigan, New Hampshire, Vermont) have put regulations in place that restrict biosolid use and disposal based on PFAS levels; these regulations include testing requirements prior to land application, monitoring regimes, effluent standards, pretreatment requirements, and other measures.[242] Many other states have regulations governing the use and disposal of biosolids that were written to mitigate the introduction of nutrients, contact with pathogens, and other issues and were not designed to address PFAS per se.[243] Per the EPA's PFAS Roadmap, the agency plans to release " a full risk assessment on PFOA and PFOS in biosolids for release in 2024."[244]

Drinking Water

States that are at the forefront of PFAS destruction and regulation efforts will likely drive the market for PFAS destruction solutions. The EPA typically sets maximum contaminant levels (MCLs), which specify the highest level of a contaminate that is permissible in drinking water.[245] In the absence of MCLs for PFAS, about half of all states (24) have implemented their own MCLs, other regulations, guidance, health advisories, and/or notification levels for PFAS levels in drinking water through legislation and state agency rulemaking.[246] These states are primarily in Northeast, Great Lakes, and/or Mid-Atlantic and West Coast regions, as shown in the figure below from the advocacy group Safer States. (Note that Nevada should also be shaded in turquoise/light blue for the purposes of this report.

In the absence of MCLs for PFAS, about half of all states (24) have implemented their own MCLs.

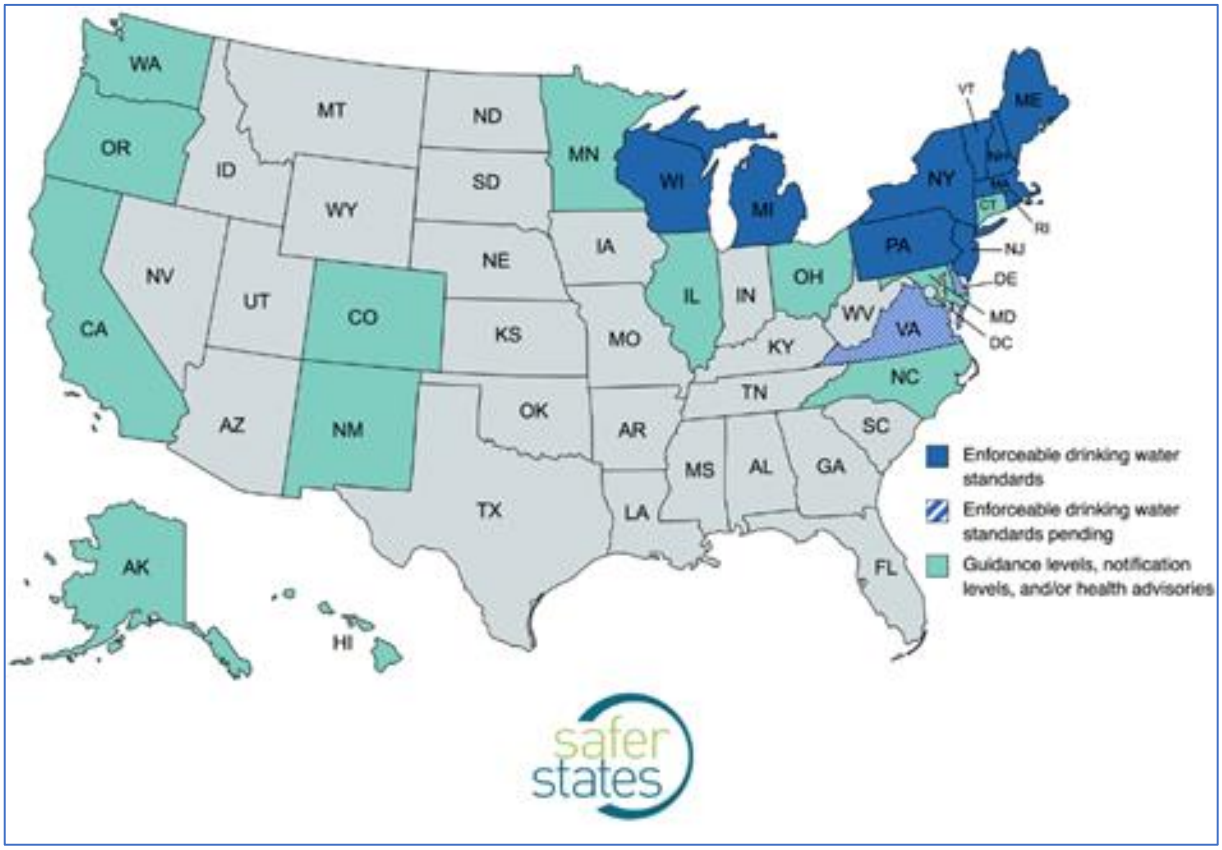


Figure 18: PFAS Drinking Water Standards and Guidance by State
Source: Safer States (July 25, 2023)[247]

As of July 2023, enforceable state drinking water rules or Maximum Contaminant Levels (MCLs) for PFAS in drinking water are in place in 10 states—Maine, Massachusetts, Michigan, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Wisconsin.[248] Another two states, Delaware and Virginia, are in the process of establishing them.[249] 14 other states have developed guidance levels, notification levels, and/or health advisory levels instead; these are Alaska, California, Colorado, Connecticut, Hawaii, Illinois, Maryland, Minnesota, Nevada,[250] North Carolina, New Mexico, Ohio, Oregon, and Washington.[251] Three states (Pennsylvania, Rhode Island, and Wisconsin) implemented standards or MCLs for PFAS in drinking water during 2022 or 2023, with the regulatory focus remaining on PFOA and PFOS.

Further detail about these recent changes is available from ITRC (Interstate Technology and Regulatory Council)'s PFAS Water and Soil Values Table, updated in June 2023, and from state agencies linked to by ECOS (Environmental Council of the States). For further information about the basis of various states' PFAS level rules and guidelines, refer to the

ECOS report Processes & Considerations for Setting State PFAS Standards[252] or section 8 of ITRC's PFAS Technical and Regulatory Guidance Document.[253]

The EPA's proposed PFAS National Primary Drinking Water Regulation (NPDWR) issued in March 2023 would create enforceable MCLs and non-enforceable Maximum Contaminant Level Goals (MCLGs) for six PFAS (PFOA, PFOS, PFNA, PFHxS, PFBS, Gen-X) in drinking water, treating PFOA and PFOS as individual contaminants and the others as a PFAS mixture.[254] Attorneys general from 16 states and the District of Columbia filed comment in May 2023 in support of the EPA's proposed PFAS drinking water regulations. The group primarily represented states that have implemented their own PFAS standards (Maine, Massachusetts, Michigan, New Jersey, New York, Pennsylvania, and Wisconsin) or guideline levels (California, Colorado, Connecticut, Illinois, Maryland, North Carolina, and Oregon), with the addition of Delaware and Arizona.[255] While no state's drinking water standards or guidance levels for PFOS and PFOA are as low as the 4.0 ppt MCL the EPA proposed for PFOS and for PFOA in March 2023, most (16 out of 20) have state-specific PFAS limits for drinking water that are well below the EPA's 2016 LHA of 70 ppt for PFOA and PFOS. Only one state (Nevada) has PFOA and PFOS limits above the 2016 advisory, and four (Alaska, New Mexico, Ohio, and Wisconsin) use the EPA's previously recommended 70 ppt limit.

The 20 states that have not established their own limits on PFAS levels in an environmental medium (Alabama, Arizona, Arkansas, Idaho, Kansas, Louisiana, Mississippi, Missouri, Nebraska, North Dakota, Oklahoma, South Carolina, South Dakota, Tennessee, Utah, Virginia, West Virginia Wyoming) span the Southeast, Midwest, Southwest, and Rocky Mountain regions. These states may use the EPA's 2016 Lifetime Health Advisories (LHA) for PFOA and PFOS as the basis for state environmental and public health action, but they have not published criteria for addressing levels that exceed the 2016 LHA limits.[256]

According to ECOS's March 2023 report on its ongoing survey of state environmental and health agencies, many states have been waiting for federal standards to be finalized. Some states (e.g., Arizona, Arkansas, Idaho, Indiana, Iowa, Kansas, Maryland, Missouri, New Mexico, North Carolina, Oklahoma, Utah) have restrictions that prohibit them from setting drinking water or groundwater standards in one or more environmental medium that are stricter than federal guidelines, which may discourage efforts to enact other state-specific limits on PFAS. Other state agencies report that capacity and resource limitations prevent them from effectively regulating PFAS without federal support, naming barriers such as funding, legislative support, legal authority, technical expertise, adequate sampling or data collection, and access to labs certified to test PFAS. Even among state agencies that lack the authority or capability to establish enforceable PFAS limits or guidance, however, other efforts to share information with the public and monitor and remediate PFAS in drinking water and other environmental media are underway, such as the expansion of public water system and private well sampling and formation of interagency PFAS task forces to coordinate communication and emergency response within a state.[257]

Based on the state legislative activity and agency rulemaking described above and on the known PFAS contamination maps from EWG (Environmental Working Group) (updated June 2022), Northwestern University's PFAS Project Lab (updated May 2023), and USGS's PFAS in U.S. Tap Water Dashboard (updated July 2023), the regulations and current initiatives in 3 states—Minnesota, Oklahoma, and Louisiana—are discussed in further detail below. Minnesota is an example of a state in which a long-term PFAS manufacturer resides, Oklahoma illustrates the complexities of water treatment on tribal lands, and Louisiana highlights the risk PFAS poses to aquaculture.

4.1. Minnesota

While Minnesota has not set MCLs or other standards for PFAS in drinking water as other influential PFAS-regulating states have done, it has been at the forefront of PFAS legislation and rulemaking in other areas, state-specific planning for future PFAS regulation and meditation, and statewide monitoring of PFAS levels.[258] Much of Minnesota's PFAS control efforts have emerged from 3M's decades of PFAS production and use in facilities on the east side of Minneapolis, where 3M is based. A significant spike in rates of cancer and other major diseases that have been associated with high levels of PFAS exposure in that area has garnered the most national attention and formed the basis for the state's suit against 3M, which was settled in 2018.[259, 260, 261, 262, 263]

One reason Minnesota has been recognized as a leading state in the PFAS response effort is the state's passage in April 2023 of what is said to be the broadest PFAS control policy package to date[264, 265] and the most restrictive PFAS regulations thus far.[266, 267, 268] [269] These laws are aimed at limiting or phasing out the use of PFAS in consumer products by requiring disclosure of PFAS in products by 2026, restricting the unnecessary use of PFAS in products by 2032, and banning their use in 13 types of products (e.g., cookware, menstrual products).[270] Massachusetts, New York, and Vermont are thought to be likely to follow Minnesota's lead.[271]

The extent of Minnesota's PFAS regulation efforts are laid out in *Minnesota's PFAS Blueprint* (2021) and implementation timeline for 2022-2024. In terms of wastewater, Minnesota's PFAS Monitoring Plan (2022) encompasses municipal wastewater treatment facilities among other entities and media. ECOS summarizes Minnesota's program as follows:

> “The Minnesota Pollution Control Agency (MPCA) selected WWTPs with identified significant industrial users to begin understanding PFAS impacts coming into the treatment plants. The voluntary monitoring will be completed in 2023 and 2024 to help determine influent concentrations of PFAS as well as help identify potential sources of PFAS entering municipal wastewater treatment systems. There will also be a focused effort to develop a PFAS pollutant management plan for source reduction at these facilities.”[272]

4.2. Oklahoma

To date, Oklahoma does not appear to have implemented any state restrictions or advisories on PFAS levels in any medium, such as wastewater or drinking water or in relation to surface water, groundwater, soil, air, or wildlife/fish consumption. Oklahoma has a restriction in place that prohibits the state from setting drinking water or groundwater limits stricter than those set by the EPA, according to an ECOS (Environmental Council of the States) survey from March 2023.[273] There are no adopted bills related to PFAS that are recorded in Safer States’ Bill Tracker, but two are currently under consideration. S.B. 877 would limit land application of contaminated septage, and S.B. 874 would require the disclosure of contaminated biosolids under certain conditions. Implementation of PFAS limits in wastewater and other waters would be handled by Oklahoma’s Department of Environmental Quality (DEQ).

The state of Oklahoma’s DEQ, for its part, in response to the EPA reviewing or developing several ELGs (effluent limit guidelines) including one for PFAS, said in its 2022 Annual Report that, “Any changes will result in additional workload for WQD [Water Quality Division] staff and more restrictive permit limits for the regulated community.”[274] As with other states, however, Oklahoma was recently allotted funds by the EPA in fiscal year 2023 for water treatment capitalization project addressing emerging contaminants, such as PFAS. Oklahoma’s allotment is $10,711,000.[275]

Oklahoma is unique in the high percentage of tribal lands that make up the state (see shaded areas in the map below), but the complexities of Clean Water Act-related rulemaking and enforcement on tribal lands is common to virtually all states. This is relevant to wastewater regulation because the EPA “directly implements the CWA [Clean Water Act] in Indian country and currently implements most programs,”[276] as the EPA does for most federal environmental programs in Indian country.[277]

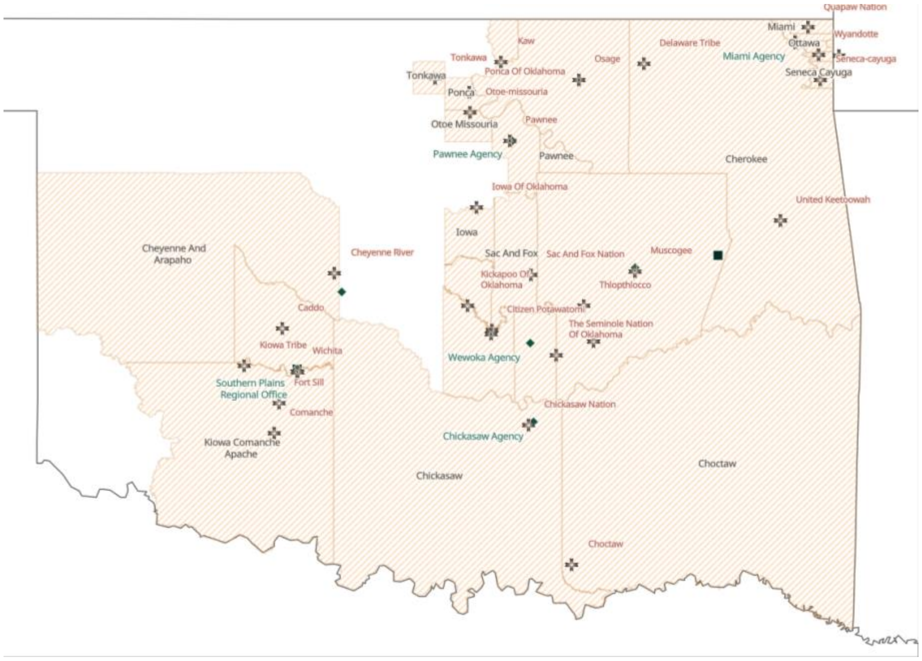


Figure 19: Oklahoma - U.S. Domestic Sovereign Nations: Land Areas of Federally Recognized Tribes
Source: Bureau of Indian Affairs[278]

Like states, tribal governments can apply to EPA to be delegated the authority to carry out some environmental regulatory programs, administrative functions, and grant programs. This includes some CWA components such as the Water Quality Standards (WQS) and **NPDES (National Pollution Discharge Elimination System) programs**, but no tribes currently have delegated authority for NPDES programs, and only one tribe among Oklahoma's 39 federally-recognized tribes has been approved to manage a WQS program.[279] Per EPA, "WQS are the foundation of the water quality-based pollution control programs required by the CWA," including components of NPDES programs.[280] Oklahoma's EPA-approved WQS do not apply to waters in Indian country, as is true of most state WQS, so tribes that have not set.[281]

Some tribes in Oklahoma have made formal agreements with the states to set and enforce various CWA provisions, while in other cases, the state of Oklahoma has been the *de facto* regulatory and enforcement body.[282] In short, the question of who has jurisdiction over environmental regulation and enforcement is incredibly complicated when it comes to tribal lands. This has created a gap in regulations and water protections for some. The EPA announced an allotment of funds to tribal lands in June 2023 for expanding capacity to treat water for emerging contaminants.[283]

4.3. Louisiana

As with Oklahoma, no legislation or regulations pertaining to PFAS contamination of wastewater, or any other media were found. High levels of PFAS have been detected in drinking water supplies in southern Louisiana, particularly in the part of southeast Louisiana known as "Cancer Alley."[284, 285] In January 2023, Rebecca Malpass, representing a local environmental advocacy group The Water Collaborative, noted, "We found numbers of PFAS that were 200 to 268 times what the EPA said was safe for our drinking water."[286] Two-thirds of Louisiana gets its drinking water from ground water sources.[287]

> **We found numbers of PFAS that were 200 to 268 times what the EPA said was safe for our drinking water."**

At the same time, Louisiana has a thriving freshwater fish (mainly catfish) and crustacean aquaculture industry.[288] Louisiana is the top state for crawfish farming, wild capture, and sales in dollars.[289, 290] Louisiana's crawfish farms produce about 90% of crawfish farmed in the U.S.[291] These farms rely on groundwater as well to supply their pools. According to the Louisiana State University AgCenter, "About 40 percent of this water requirement will be supplied by precipitation, but the balance (60 percent) must be provided by surface water or groundwater."[292] In Louisiana, as in other places, the direct connections between different water and their uses, as well as the broader connections through the water cycle, mean that PFAS contamination affects many areas, people, and industries.

5.0 PFAS Destruction in Recent Research

There are many research studies focused on ongoing and emerging potential PFAS destruction technologies. The EPA has funded a number of research studies, in addition to their own research initiative, the PFAS Innovative Treatment Team (PITT), which was formed in 2020 to focus on the problem of "disposal and/or destruction of PFAS-contaminated media and waste." The group examined emerging and ongoing technologies for technology effectiveness, as well as "feasibility, performance, and costs." This work centered around four technologies: **electrochemical oxidation, mechanochemical degradation, pyrolysis and gasification, and supercritical water oxidation.**[293]

Electrochemical oxidation, supercritical water oxidation, pyrolysis and gasification were also mentioned in a recent presentation published by the EPA (PFAS Fate and Remediation: Treatment Methods and Residual Waste Streams) along with other technologies **(biological processes, hydrothermal processes (hydrothermal liquefaction, hydrothermal oxidation, sub-critical water oxidation), electron beam irradiation (E-beam), advanced oxidation/reductive processes, membrane distillation, pyrolysis and gasification, and combined systems**.[294]

There are studies which review/examine the state of current potential PFAS destruction technologies such as **thermal/hydrothermal treatments[295], mechanochemical degradation[296], phytoremediation[297], advanced oxidation/reduction processes[298], electrochemical oxidation[299], low-temperature plasma treatment[300], ultrasound/sonolysis[301],** as well as overarching studies on the status of PFAS destruction.[302, 303]

There is a vast amount of research on PFAS destruction technology and some of the literature for commonly explored technologies, which have been illuminated by the EPA follows.

5.1. Electrochemical oxidation

Electrochemical oxidation oxidates pollutants with electrical currents that have traveled through a solution.[304] This process is illustrated in the following image.

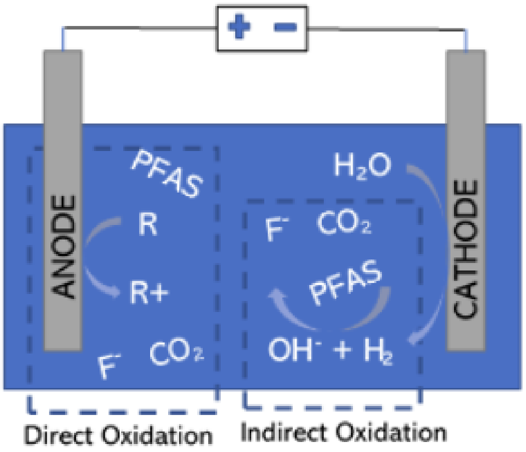


Figure 20: “Mechanisms of Electrochemical Oxidation”
Source: U.S. Environmental Protection Agency[305]

Problems associated with this technology include:

- Potential of toxic byproduct production[306]
- Some PFAS will undergo only partial destruction[307]
- Lower effectiveness caused by a growth of minerals on the anode[308]

- Electrode cost[309]
- Volatilization of contaminants can occur[310]
- This technology isn't effective for the destruction of low concentrations (in parts per billion) of PFAS (in long and short chains)[311]

According to Mukherjee et al., "additional research is needed to understand the synergistic or antagonistic removal mechanism of PFAS in the presence of mixtures of PFAS (i.e., the simultaneous presence of shorter and longer chain PFAS)."[312]

While downsides to this technology have been outlined, the EPA still identifies electrochemical oxidation as having potential promise in particular situations since it can use smaller amounts of energy for PFAS destruction, as opposed to thermal incineration.[313]

5.2. Pyrolysis and gasification

Pyrolysis is defined as "a process that decomposes materials at moderately elevated temperatures in an oxygen-free environment" while "gasification is similar to pyrolysis but uses small quantities of oxygen, taking advantage of the partial combustion process to provide the heat to operate the process." A research brief published by the EPA in 2021 noted that pyrolysis or gasification have potential for PFAS destruction in comparison to various sewage sludge incineration methods. These technologies could work by fragmenting PFAS "into inert or less recalcitrant constituents" but this technology could be challenging to implement due to gaps in data and cost.[314]

According to a paper presented at the 2023 WEF/IWA Residuals and Biosolids Conference in Charlotte, NC in 2023, "Pyrolysis will become increasingly valuable as biosolids management options are expected to be further constrained by state and national policies including landfilling bans, land application restrictions, competition for compost capacity, and federal PFAS regulations." The paper presents a case study on the Rialto Bioenergy Facility (RBF) in Rialto, CA. The facility processes dewatered biosolids derived from municipal WWTPs. Pyrolysis and drying creates a biochar product from Class B Biosolids for application as fertilizer. The pyrolysis method utilized at this facility destroys PFAS.[315]

Recent research has indicated a knowledge gap when it comes to "PFAS fate and removal" when pyrolysis is applied to biosolids.[316]

5.3. Hydrothermal alkaline treatment reactor (HALT)

Hydrothermal alkaline treatment reactor (HALT) technology "has previously been shown to destroy a wide range of PFAS compounds with a high degree of destruction and defluorination."[317] This technology has been proven to destroy not only long-chain PFAS, but also short-chain in Aquagga's HALT technology in recent research funded by the EPA.[318] There have been studies identifying the promising nature of HALT technology in PFAS[319, 320] and PFOS[321] destruction.

A 2023 study involving HALT technology identified a knowledge gap for treating PFAS contaminated soil and groundwater after aqueous film-forming foam (AFFF) had been used, as well as a lack of study in PFAS destruction tactics for direct soil treatment.[322]

5.4. Supercritical water oxidation

Supercritical water oxidation (SCWO) is defined as "a process that can be utilized to destroy hazardous waste compounds."[323] The following image illustrates how SCWO works in relation to the temperature and pressure of water.

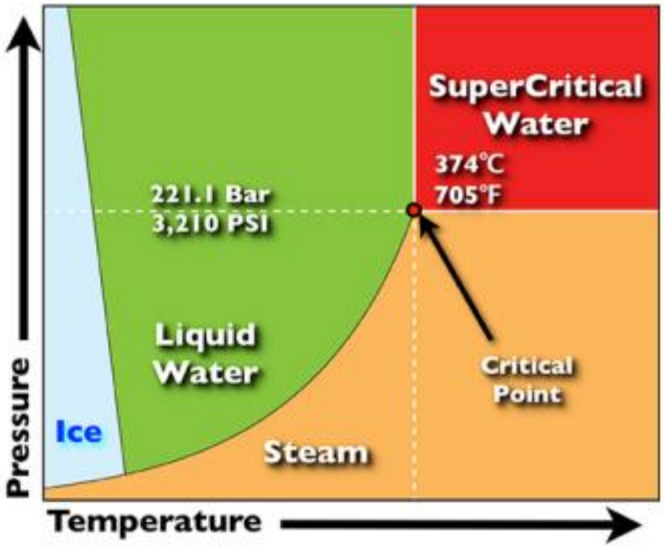


Figure 21: "SCWO Reactions Occur Above the Critical Point of Water"
Source: U.S. Environmental Protection Agency[324]

There have been several recent research studies conducted on SCWO that prove its potential as a PFAS destruction technology, with 99% or more PFAS reduction.[325, 326, 327, 328]

The EPA has identified gaps in SCWO research, including the possibility of "system degradation and maintenance issues" that come with the conditions of the SCWO process.[329, 330] More challenges and gaps in research include the high energy output which comes at a steep cost and the fluoride salts that are formed in this process which result in lowering system performance and reactor plugging.[331, 332] It is also possible that necessary precautions for the health of workers, controls for emissions, and reactor care may be needed when fluorine turns to corrosive hydrofluoric acid (HF). Adding chemical additives like alkaline substances may help by neutralizing the acidic environment.[333]

5.5. Ultrasound / sonolysis

Ultrasound technology is a frequently explored solution in PFAS degradation studies. The EPA is currently funding ongoing research that will study, in part, the way leachate conditions have an influence on the success of ultrasound technology for PFAS degradation which will play a role in shaping the way this technology could operate in landfills.[334]

Sonolysis shows up in literature as an ultrasound technology that has potential use for PFAS destruction. A 2021 study illustrated that sonolytic treatment can defluorinate and degrade PFAS in Aqueous Film-Forming Foam (AFFF) Investigation Derived Waste (IDW) and concentrated PFAS mixtures without creating disinfection byproducts.[335]

One 2023 study examines the effects of 1001,000 kHz, high frequency ultrasound, as it affects aspects like reactor configuration, liquid height, frequency, and power density. The technology in this study is applied to remediation samples of landfill leachate concentrate and firefighting foam. The potential for use of this technology in industrial applications is explored.[336] Another recent study applied low and high frequency ultrasound technology for the desorption and degradation of soil contaminated with PFAS and PFOS. Their results indicated lower levels of PFAS concentration in soil, which was contaminated with PFAS artificially, but "significant degradation" was unsuccessful. The study's results indicated an efficacy for PFAS removal in solids, but in a solid-liquid slurry solids may have an adverse effect on the ultrasonic cavitation which restrains desorbed PFAS degradation.[337]

A recent article notes that "the impact of ultrasonic parameters on PFAS degradation must be better understood to transition the technology from the research discovery phase to field application" but their study results indicate sonolysis is a viable option for the treatment of PFAS in concentrated waste.[338]

5.6. Additional technologies

Additional technologies under study for PFAS destruction include various means of ultraviolet (UV) radiation[339, 340, 341, 342], plasma treatment[343], ball milling[344], and thermal destruction.[345]

5.7. Summary and areas that need more research

Gaps in PFAS destruction technology research have been identified in several studies across this subject. Overarching gaps related to defluorination reactions, and technological gaps within pilot tests, water matrix effects and cost analysis exist which hinder treatment technology comparisons.[346]

Further research needs were identified in several areas, such as:

- Electrochemical oxidation in removal of low concentrations of long and short chain PFAS[347]
- More research is needed for pyrolysis and gasification data and cost before implementation[348]
- PFAS fate and removal using pyrolysis treatment on biosolids is unclear[349]
- A gap in research relating to the treatment of PFAS contaminated soil and groundwater after aqueous film-forming foam (AFFF) was identified, as well as an absence of information in PFAS destruction tactics for direct soil treatment[350]
- SCWO technology may cause “system degradation and maintenance issues” due to the conditions that come along with its operation.[351, 352]
- SCWO involves a high energy output which comes at a high cost, in addition to the fluoride salts that are formed during operations. These salts lower system performance and reactor plugging.[353, 354] SCWO may become safer if chemical additives are implemented into the process[355]
- Ultrasound parameters and their effect on PFAS degradation need to be further understood[356]
- More research on using an hBN (Hexagonal boron nitride) photocatalysis with ultraviolet radiation[357]
- Products of incomplete combustion (PIC) may need to be identified in addition to destruction efficiency (DE) to ensure complete PFAS destruction.[358]

6.0 Industry Initiatives

There are a number of industry commercialization and R&D activities underway for PFAS destruction technologies. This section includes examples of these initiatives.

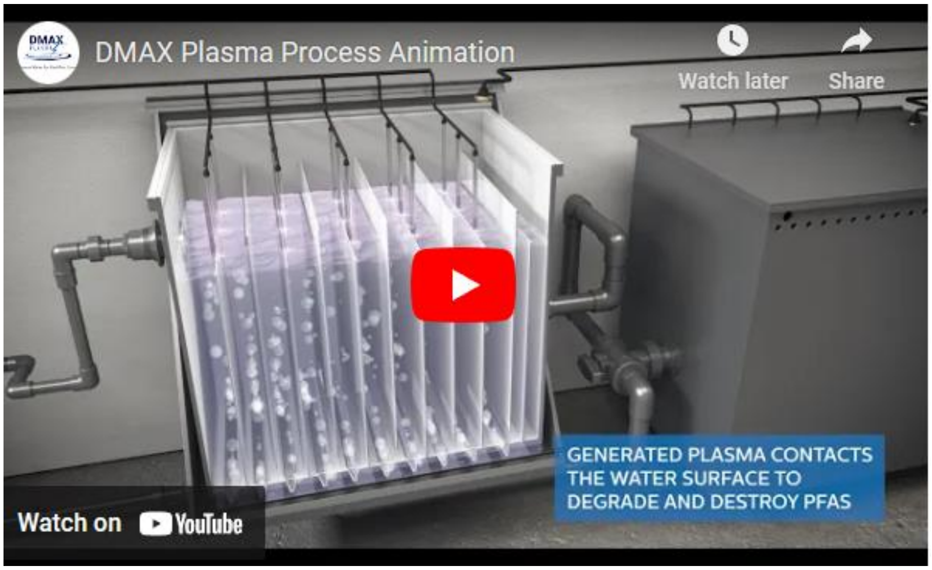
6.1. DMAX Plasma Inc.

DMAX Plasma Inc.'s technology was created by three professors at Clarkson University, where the Center for Air and Aquatic Resources Engineering and Sciences (CAARES) Lab is accredited with the Department of Defense Environmental Laboratory Accreditation Program (DoD ELAP) for analysis on PFAS. These accredited labs are able to conduct testing for DoD environmental restoration programs. CARRES, in particular, has had several research grants with the DoD and EPA for PFAS destruction in soil and water. DMAX Plasma originated as a result of these grants.[359]

The inception of the limited liability company was in 2014, with the intent of commercializing its plasma technology.[360] The small company, based out of Potsdam, NY, has five employees listed on its LinkedIn page[361] and is in the process of providing plasma reactors to their expected customers for validation.[362]

The ECo-PRe™ system "destroys PFAS by producing electrons and ions which react with PFAS, directly defluorinating and breaking the carbon-fluorine bonds into smaller molecules which are then oxidized and further reduced to harmless compounds."[363] The technology is predicated on electrical discharge plasma technology.[364]

Additional information about DMAX Plasma's PFAS destruction process is detailed in the following video, which is linked below.



GENERATED PLASMA CONTACTS THE WATER SURFACE TO DEGRADE AND DESTROY PFAS

Video can be accessed by following this link

Figure 22: "DMAX Plasma Process Animation"

Source: DMAX Plasma[365]

The ECo-PRe™ system is field proven[366] and was part of a successful field demonstration for the Air Force in 2019 which proved the technology's ability to meet EPA's PFAS standards at the time, while the technology continued to undergo testing.[367] Results of the field test were published in *ACS ES&T Water* in 2021. Before this, evidence of the technology's ability to reduce PFAS concentrations in Investigation- Derived Waste (IDW) was published in 2019. DMAX Plasma is also in the midst of a study for the DoD to test the effectiveness of electrical discharge plasma technology for PFAS degradation in aqueous film forming foam (AFFF).[368]

6.2. Revive Environmental/Battelle

Battelle, headquartered in Columbus, OH,[369] has more than 40,000 employees.[370] Revive Environmental, which is also headquartered in Columbus, OH, is owned by Battelle and Viking Global Investors.[371, 372] Revive Environmental started business in early 2023 to "deploy" Battelle's PFAS Annihilator and GAC Renew technology, while Battelle continues to pursue applied research and development activities.[373]

Battelle created the PFAS Annihilator,[374] a product dubbed the "first-to-market commercial destruction of forever chemicals."[375] This product is currently implemented at eleven Crystal Clean Water Treatment sites across the U.S.[376] as well as on contract with NH to "to remove and dispose of 10,000 gallons of aqueous film-forming foam (AFFF)" from municipal firehouses."[377]

The PFAS Annihilator works by using supercritical water oxidation (SCWO) technology for PFAS destruction in Aqueous Film Forming Foam (AFFF), contaminated wastewater, and landfill leachate. The pressure and high temperature, carried out through mobile technology, destroys PFAS in a matter of seconds leaving only water behind.[378] The technology provides >99.9% destruction of long- and short- chain compounds, in addition to ultra-short chain compounds.[379]

The following graphic outlines the PFAS Annihilator technology process:

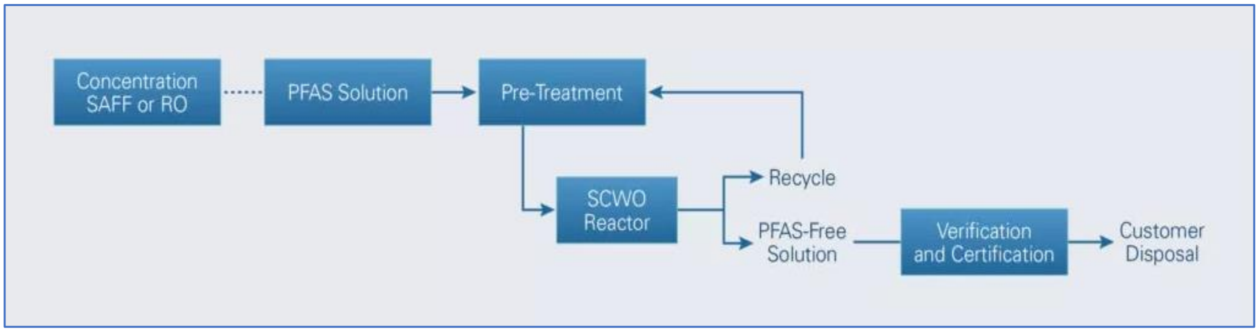


Figure 23: PFAS Annihilator Technology Process

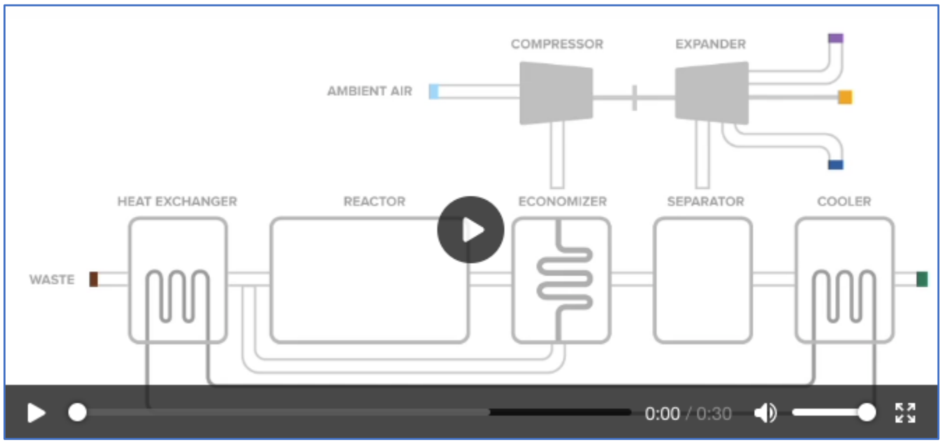
Source: Revive Environmental[380]

This technology has been proven effective in destroying "99.99% of PFAS in landfill leachate and AFFF, with concentrations in the millions of parts per trillion" during customer engagements.[381] According to Battelle, water that's been treated by the PFAS Annihilator can be tested to ensure its compliance before that water is discharged.[382]

6.3. 374Water, Inc.

374Water identifies as "a global cleantech, social impact company." The company, headquartered in Durham, NC,[383] has less than 50 employees according to their website and LinkedIn page.[384, 385]

374Water's AirSCWO™ technology "is a physical-thermal process powered by water above its critical point (374°C and 221 bar) and air that yields a highly effective oxidation reaction that completely eliminates organic compounds," otherwise known as SCWO.[386] A detailed look at the AirSCWO™ system can be found in the following linked video.



Video can be accessed by following this link

Figure 24: AirSCWO™ System Process

Source: 374 Water[387]

In 2022, the U.S. Navy chose 374Water's commercial AirSCWO technology for a demonstration at a Naval installation. The technology has been tested and proven effective at PFAS destruction in a number of media (i.e., lime-stabilized sludges, Aqueous Film Forming Foam (AFFF), and granular activated carbon and ion exchange resins).[388]

6.4. Aclarity

Aclarity has less than 20 employees according to their website and LinkedIn page.[389, 390] The company is located in Mansfield, MA and partnered with Xylem, Heartland Water Technology, Burnt Island Ventures, De Nora, and DCVC.[391]

Aclarity's PFAS destruction technology uses an electrochemical process to break down contaminants, detailed in the following figure.[392]

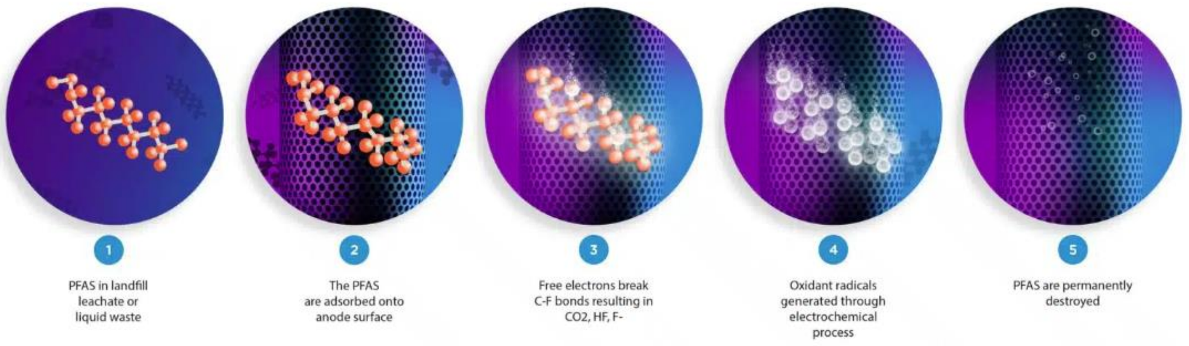


Figure 25: "How it Works: Aclarity PFAS Destruction Technology
Source: Aclarity[393]

In early 2023, it was announced that Aclarity's modular PFAS destruction technology was successful in destroying PFAS contaminated landfill leachate at a customer's site. Continuous destruction reaching 99% was verified by a third-party lab.[394]

6.5. Claros Technologies

Claros Technologies, based out of Minneapolis, MN, lists 22 employees and three board members, including the CEO, on their website.[395]

Claros Technologies' Elemental™ PFAS Destruction technology (pictured below) destructs, long, short, and ultrashort PFAS substances using a proprietary photochemical process. The low-energy system operates using atmospheric pressure at room-temperature to destroy more than 99% of PFAS compounds in the following applications:[396]

- "Wastewater and landfill leachate
- Concentrates from ion-exchange resins, reverse osmosis, activated carbon or foam fractionation systems
- Fire fighting foams and their runoffs"[397]

Figure 26: Elemental™ PFAS Destruction System
Source: Claros Technologies[398]

Claros Technologies' technology is patented, so validation of its PFAS destruction results can be difficult to confirm,[399] but the company offers its own testing & analysis services which are detailed in the following linked video.

Figure 27: "Claros Technologies Analytics and Support Services"
Source: Claros Technologies[400] *Video can be accessed by following this link*

In July 2023, it was reported that Claros is preparing to operate at a more substantial, commercial scale in the upcoming months.[401]

6.6. General Atomics

General Atomics, headquartered in San Diego, CA,[402] has more than 12,500 employees.[403] The company's iSCWO (Industrial Supercritical Water Oxidation) is a commercial system that "destroys concentrated PFAS waste directly from a source (e.g., Aqueous Film Forming Foam (AFFF)) as well as PFAS waste containing other co-contaminants (e.g., carbon tetrachloride, solvents, etc.)."[404] A visual representation of this technology is depicted in the illustration that follows.

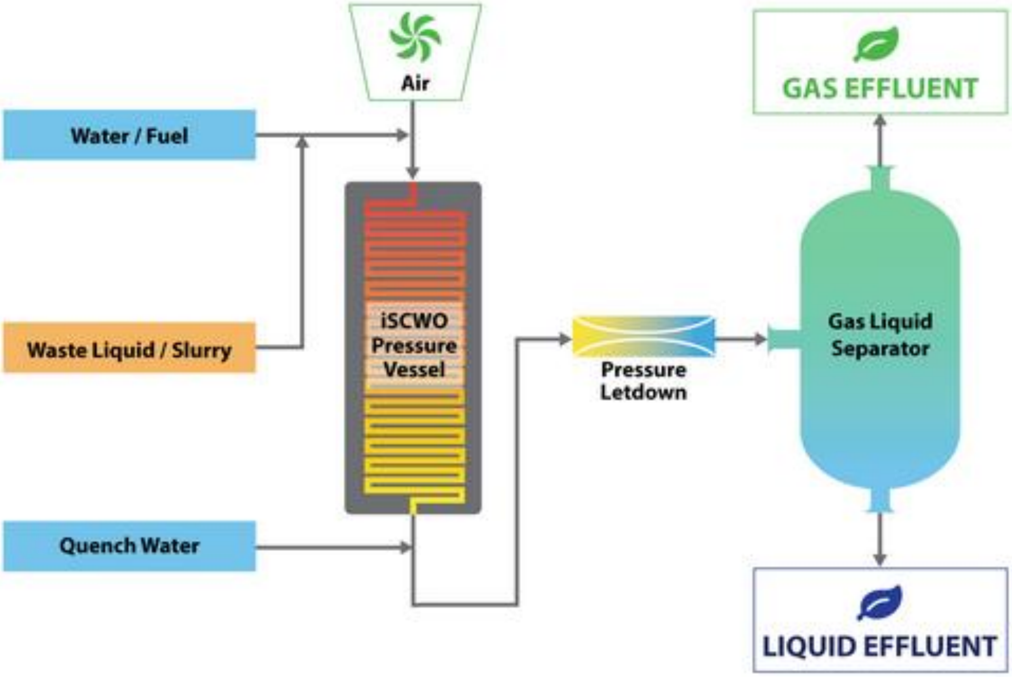


Figure 28: iSCWO System
Source: General Atomics[405]

This technology has been tested and verified by the EPA that it's effective in destroying more than 99.99% of PFAS/Aqueous Film Forming Foam (AFFF). According to General Atomics, "This is first-ever test documenting the successful use of a commercial industrial SCWO system for the destruction of PFAS." The results, published by the EPA, can be found by following this link.[406]

General Atomics' iSCWO systems were deployed starting in 2012. The company facilitates waste testing through their continuous flow test facility in San Diego, CA.[407]

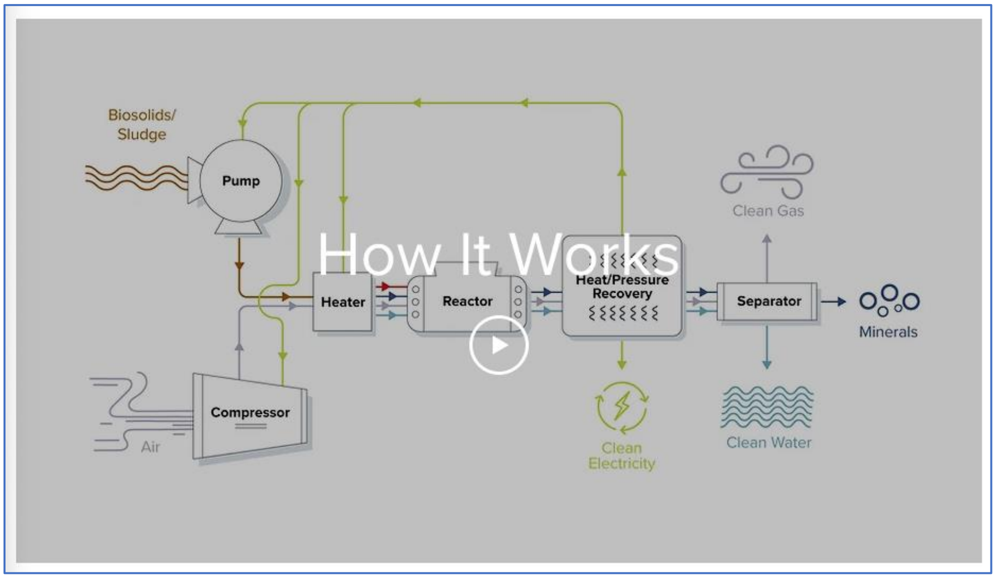
6.7. OXbyEL Technologies

OXbyEL Technologies, based out of Phoenix, AZ,[408] has received a Phase 1 EPA/ SBIR Grant and contract (now complete), in addition to a National Science Foundation (NSF) grant. The company is also in the middle of two projects for the U.S. Air Force.[409]

OXbyEL Technologies is in the midst of commercializing their proprietary total organic fluorine (TOF) Electrolyzer which is based on electro-oxidative technology.[410] The small company[411] has created the TOF Electrolyzer which "incorporates a scalable, divided radial-field unit cell architecture with a low-cost anode electrocatalyst that provides direct electron transfer oxidation and electro-sorption for the highest rates of mineralization. The radial field configuration provides two degrees of freedom which is adaptable to large-scale industrial use."[412]

6.8. Beyond the Dome

Beyond the Dome, based out of San Francisco, CA,[413] has created a contaminant destruction technology based on SCWO.[414] According to information from the Small Business Innovation Research (SBIR) program, the company has four employees.[415] More information on how Beyond the Dome's technology works can be found in the following video linked below.



Video can be accessed by following this link

Figure 29: Beyond the Dome: How It Works

Source: Beyond the Dome[416]

6.9. Aquagga, Inc.

In 2022, it was reported that Aquagga, a Seattle-based company focused on PFAS destruction, has 10 employees working full time and intends to become a B Corporation.[417] The startup was formed in 2019 and will be commercializing their technology which originated at the Colorado School of Mines.[418, 419]

Aquagga's technology is based on hydrothermal alkaline treatment (HALT) that "harnesses the unique properties of hot, compressed water, the systems break the strong carbon-fluorine bonds that hold PFAS together." The company offers mobile treatment products: 'Pilot' Series, 'Steed' Series, and 'Stampede' Series and their technology has been validated by a number of organizations and academic institutions including the University of Washington, University of Alaska Fairbanks, Idaho National Laboratory, and Colorado School of Mines.[420]

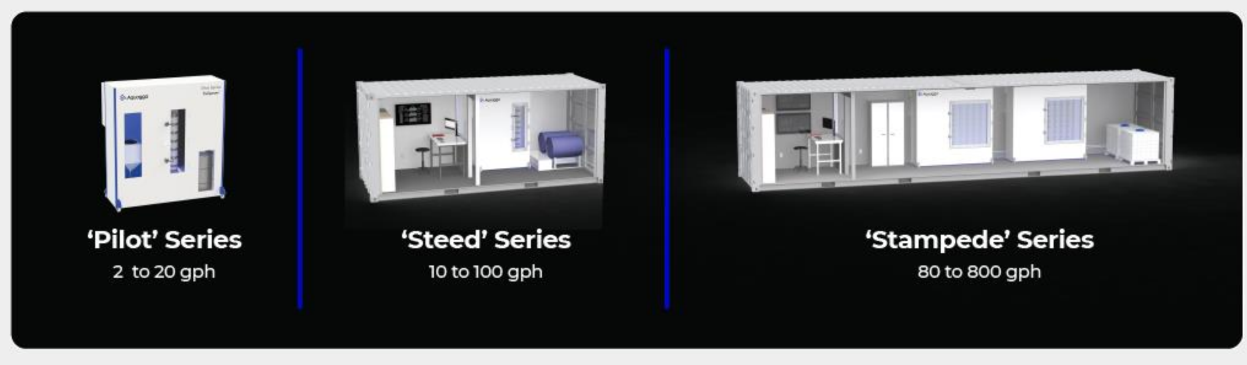


Figure 30: Aquagga Products
Source: Aquagga[421]

6.10. U.S. Military

In early 2023 it was reported that the U.S. military will be testing a PFAS destruction technology that combines hot air under pressure with water on a Navy base, in addition to two Air Force bases. The tests will be conducted on contaminated groundwater and will be an aspect of the military's hunt for PFAS destruction technology.[422]

In addition, Fort Leavenworth was home to a two-week field demonstration where PFAS destruction technology was tested. This demonstration of a new technology that will treat groundwater and provided "98% destruction of PFOA and 86% destruction of PFOS with similarly high destruction of many resultant shorter chain PFAS, but on a small scale (low throughput)." Fort Leavenworth and U.S. Army Environmental Command (USAEC) already implemented a successful four-vessel granular activated carbon filtration system next to a water treatment plant with the Kansas Department of Health and Environment.[423]

7.0 Summary and Conclusion

Numerous technologies aimed at destroying PFAS exist. In 2020, EPA's **PFAS Innovative Treatment Team (PITT)** examined the feasibility, performance and cost associated with four technologies: Electrochemical oxidation, mechanochemical degradation, pyrolysis and gasification and supercritical water oxidation. In the resulting briefs, research gaps were highlighted and next steps identified. Other research studies provide an overview of the state of the art with respect to emerging approaches and include thermal/hydrothermal treatments, photoremediation, low temperature plasma treatment and ultrasound sonolysis, to name a few. A summary of some of their conclusions regarding areas where further research is required is included in this report. Industry is also harkening the call for solutions and prototypes are being developed. Numerous products are mentioned in this report for review including DMAX Plasma, Inc., Revive Environmental, 374Water and numerous others. When available, video links are provided to demonstrate their process.

From a solution implementation perspective, significant challenges exist including funding, liability, availability of testing procedures and variability in regulations which take precedence at a local level.

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