United States Government Accountability Office

Report to Congressional Requesters

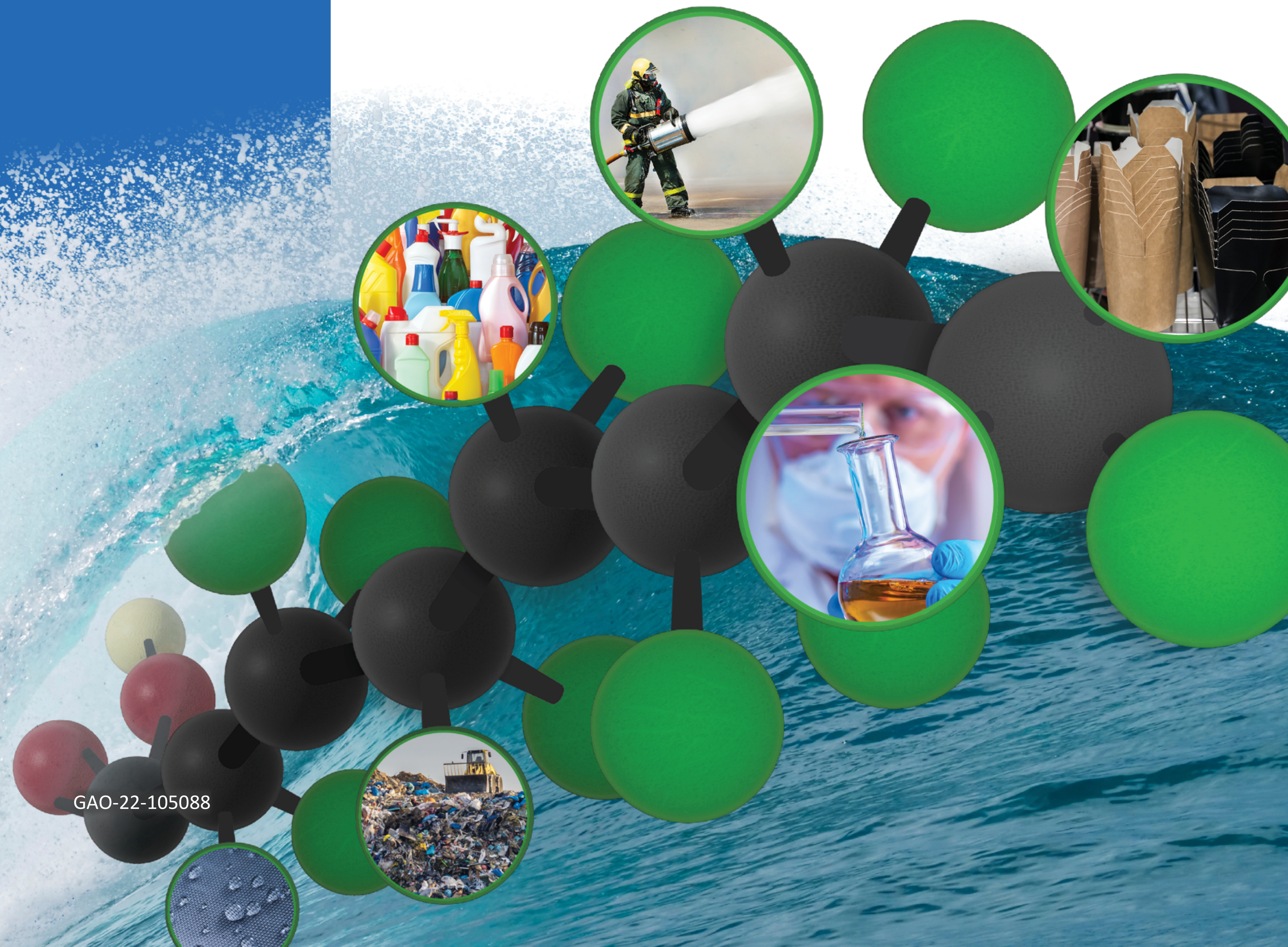
July 2022

TECHNOLOGY ASSESSMENT

Persistent Chemicals

Technologies for PFAS Assessment, Detection, and Treatment

Accessible Version



GAO-22-105088

The cover image displays a stylized representation of a PFAS molecule and various applications of PFAS.

Cover sources: GAO (chemical compound); helivideo/stock.adobe.com (wave); (images from left to right): billyhoiler/vchalup/September/bboris/Grispb/Olha/stock.adobe.com. | GAO-22-105088

Highlights of GAO-22-105088, a report to congressional requesters

July 2022

TECHNOLOGY ASSESSMENT

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Technologies for PFAS Assessment, Detection, and Treatment

Why GAO did this study

PFAS are a large group of heat and stain resistant chemicals, first developed in the 1940s. PFAS are used in a wide range of products, including carpet, nonstick cookware, waterproof clothing, and firefighting foam used at airports and military bases. PFAS can persist in the environment, including in water, soil, and air, for decades or longer. The Centers for Disease Control and Prevention has found that most people in the U.S. have been exposed to two of the most widely studied PFAS, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS). Both have been linked to human health problems.

GAO was asked to conduct a technology assessment on PFAS assessment, detection, and treatment. This report examines (1) technologies for more efficient assessments of the adverse health effects of PFAS and alternative substances; (2) the benefits and challenges of current and emerging technologies for PFAS detection and treatment; and (3) policy options that could help enhance benefits and mitigate challenges associated with these technologies.

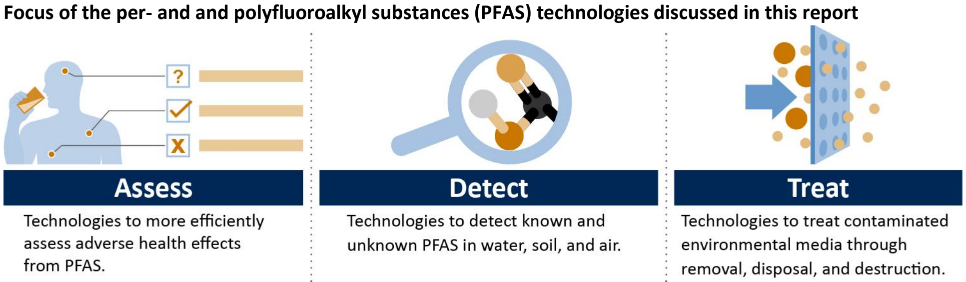
GAO assessed relevant technologies; surveyed PFAS subject matter experts; interviewed stakeholder groups including government, non-governmental organizations, industry, and academia; and reviewed key reports. GAO is identifying policy options in this report.

View GAO-22-105088. For more information, contact Karen L. Howard at (202) 512-6888 or howardk@gao.gov or J. Alfredo Gómez at (202) 512-3841 or gomezj@gao.gov.

What GAO found

Current and promising technologies and methods could accelerate assessment of human health effects caused by per- and polyfluoroalkyl substances (PFAS) and improve the detection and treatment of PFAS in the environment. However, these technologies and methods face key challenges that hinder effective management of PFAS.

Focus of the per- and and polyfluoroalkyl substances (PFAS) technologies discussed in this report



Source: GAO. | GAO-22-105088

Assessment. Technologies that may accelerate assessment of PFAS health effects include high-throughput assays—automated testing methods that rapidly evaluate a large number of chemicals—and machine learning, which may help improve on technologies that predict health effects based on the effects of similar molecules.

Detection. Current technologies for detecting PFAS can reliably quantify about 50 specific PFAS, but these technologies are unable to detect or quantify the thousands of other PFAS known to exist. EPA requires reliable samples, known as analytical standards, to develop PFAS detection methods. However, researchers and agencies are developing new detection methods that do not need analytical standards and can screen for or quantify unknown PFAS. These methods include high-resolution mass spectrometry and total fluorine analysis.

Treatment. PFAS treatment can involve removal of PFAS from contaminated media, followed either by disposal in landfills or destruction by incineration. There are full-scale, proven treatment technologies that can remove PFAS from drinking water. But these technologies also leave behind PFAS-contaminated residual materials that must be disposed of or destroyed. Emerging technologies may be more effective, but none have been demonstrated at full scale, and most are still being researched.

GAO developed three policy options (see next page) to address the following challenges with PFAS-related technologies:

- PFAS chemical structures are diverse and difficult to analyze for health risks, and machine learning requires extensive training data that may not be available.
- Researchers lack analytical standards for many PFAS, limiting the development of effective detection methods.
- The effectiveness and availability of disposal and destruction options for PFAS are uncertain because of a lack of data, monitoring, and guidance.

GAO developed the following three policy options that could help mitigate challenges associated with PFAS assessment, detection, and treatment technologies. These policy options involve possible actions by policymakers, which may include Congress, federal agencies, state and local governments, academia, and industry. See below for details on some of the policy options and relevant opportunities and considerations.

Policy Options That Could Help Enhance Benefits or Mitigate Challenges of PFAS Assessment, Detection, and Treatment Technologies

Policy Option	Opportunities	Considerations
Promote research (report p. 35) Policymakers could support development of technologies and methods to more efficiently research PFAS health risks. *This policy option could help address the challenge of limited information on the large number and diversity of PFAS, as well as a lack of standardized data sets for machine learning.*	• Promoting research on predictive methods could allow researchers to more efficiently assess PFAS classes rather than individually. • Integrating existing PFAS health information from multiple studies could result in more efficient health assessments of the wide range of PFAS. • Supporting technologies for more efficient research could also improve the assessment of alternatives to PFAS.	• Computer models for more efficiently researching PFAS may not be sufficient on their own to accurately assess health effects, because of a lack of scientific knowledge on the behavior of PFAS in the human body. • Researchers lack complete data sets to train and validate machine learning models, which are needed before such models can be used for PFAS assessment.
Expand method development (report p. 36) Policymakers could collaborate to improve access to standard reference samples of PFAS, known as analytical standards and increase the pace of method and reference sample development for PFAS detection. *This policy option could help address the challenges of a lack of validated methods in media other than water, lack of analytical standards, and cost, which all affect researchers' ability to develop new detection technologies.*	• Supporting efforts by federal and independent laboratories to develop reference samples for known PFAS could increase access to available and affordable analytical standards for researchers. • Enabling researchers to accelerate development of new detection methods for media other than water could enable researchers to discover and reliably characterize more PFAS. • Enabling development and finalization of a standard method for high resolution mass spectrometry could enable better screening and identification of PFAS in the environment.	• Private industry has been reluctant to provide analytical standards, many of which are considered proprietary, hindering the development of detection methods. • High costs for PFAS testing may deter private well owners and smaller water utilities from testing.
Support full-scale treatment (report p. 37) Policymakers could encourage the development and evaluation of full-scale technologies and methods to dispose of or destroy PFAS. *This policy option could help address the challenges of cost and efficiency of disposal and destruction technologies and a lack of guidance from regulators.*	• Supporting optimization of full-scale disposal and destruction technologies for PFAS by encouraging finalization of EPA methods could improve PFAS monitoring during incineration. • Encouraging the development of guidance to improve monitoring at landfills could help prevent future contamination. • Accelerating the development and sharing of performance and cost models for disposal and destruction of PFAS and promoting treatment could help stakeholders plan for future costs.	• Technologies for destroying PFAS could be difficult to implement at scale, due to the lack of guidance from regulators. • In the absence of effective controls, landfills may release PFAS into the environment over time. • Guidelines currently vary by a considerable amount across the U.S. and may drive up the cost of PFAS disposal and destruction.

Source: GAO. | GAO-21-105088

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Abbreviations

Abbreviation	Abbreviation phrase
AI	artificial intelligence
CDC	Centers for Disease Control and Prevention
DOD	Department of Defense
EPA	Environmental Protection Agency
GAC	granular activated carbon
HRMS	high resolution mass spectrometry
ML	machine learning
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
PFAS	per- and polyfluoroalkyl substances
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonate
QSAR	quantitative structure-activity relationship
RO	reverse osmosis
TOP	total oxidizable precursor
UCMR	Unregulated Contaminant Monitoring Rule

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
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Introduction

July 28, 2022

Congressional Requesters

Per- and polyfluoroalkyl substances, known as PFAS, are a large group of synthetic chemicals that have a wide range of uses in consumer products, manufacturing, and fire safety. They also have caused widespread environmental contamination of water, soil, and air and some have been linked to health problems in humans. According to the Centers for Disease Control and Prevention (CDC), the two most widely studied PFAS—perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS)—are detectable in the blood of most people in the U.S.[1]

You asked us to conduct a technology assessment in this area, with an emphasis on the current state of PFAS science as well as policy implications. This report discusses:

1) Technologies, such as artificial intelligence and machine learning (AI/ML), that might contribute to more efficient assessments of the adverse health effects of PFAS and alternative substances;

2) The benefits and challenges of current and emerging technologies for PFAS detection and treatment (removal, disposal, and destruction), and what gaps, if any, remain; and

3) Policy options that are available to help enhance benefits and mitigate challenges associated with PFAS assessment, detection, and treatment technologies.[2]

See appendix I for the full objectives, scope, and methodology used in this report.

We identified three policy options that could help mitigate the challenges associated with PFAS assessment, detection, and treatment technologies. Specifically, policymakers could:

- Support development of technologies and methods for more efficient research into PFAS health risks.

[1]These data are from CDC's National Health and Nutrition Examination Survey, which assesses the health and nutritional status of adults and children in the U.S. The survey, which began in the 1960s, combines interviews and physical examinations and determines the prevalence of major diseases and risk factors for diseases.

[2]In addition to this technology assessment, GAO is also conducting an audit examining the extent of PFAS contamination and related state actions; that report will be issued later in 2022.

- Collaborate to improve access to reliable samples of PFAS, known as analytical standards, and increase the pace of method and reference sample development for PFAS detection.

- Encourage the development and evaluation of full-scale technologies and methods to dispose of or destroy PFAS.

We conducted our work from March 2021 through July 2022 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background

1.1 Introduction to PFAS

Beginning in the 1940s, scientists developed a class of heat- and stain-resistant chemicals that are now used in a wide range of commercial and consumer products, including carpet, food packaging, nonstick cookware, waterproof clothing, and firefighting foams that suppress petrochemical fires and are typically used at airports and military bases.[3] According to the Environmental Protection Agency (EPA), thousands of PFAS have been identified; of these, some 1,500 distinct PFAS are known to have been in commerce in the U.S.—including fewer than 700 within the last decade. PFAS are often categorized by their chemical structure, such as the length of their carbon chains—long-chain and short-chain.[4] While both types were manufactured, there has been a reduction in use of long-chain PFAS and the two most well-known (PFOA and PFOS) have been completely phased out of manufacturing in the United States. [5]

Some PFAS have been found to bioaccumulate in animal tissues to varying degrees.[6] Thus, in addition to direct exposure to contaminated water, soil, air, or consumer goods, people can be exposed to PFAS by consuming meat, fish, or dairy products from animals that have been exposed. For most PFAS, there is limited or no information available on health effects. But according to EPA, for the PFAS that have been studied, contamination over certain levels may have a variety of adverse effects on humans, such as effects on the immune system and thyroid, liver damage, and certain kinds of cancer. The chemicals even transfer to fetuses in utero and infants through breastfeeding. Some companies in the U.S. have voluntarily phased out certain PFAS from their production processes and replaced them with chemicals that are thought to be less bioaccumulative and less toxic. Nevertheless, legacy uses and a lack of commercially viable alternatives for certain safety products, such as firefighting foams, have resulted in PFAS contamination in multiple locations across the country.

1.2 PFAS in the environment and human exposure

PFAS have a carbon-fluorine bond–one of the strongest chemical bonds in nature–which causes them to persist in the environment for many years. This report considers PFAS contamination in three environmental media: water (e.g., groundwater, drinking water), soil, and air. PFAS can enter these media from

[3]For further information on the Department of Defense's actions to address PFAS in drinking water from the use of firefighting foam at or near military installations, see GAO, *Firefighting Foam Chemicals: DOD Is Investigating PFAS and Responding to Contamination, but Should Report More Cost Information,* GAO-21-421 (Washington, D.C.: June 22, 2021).

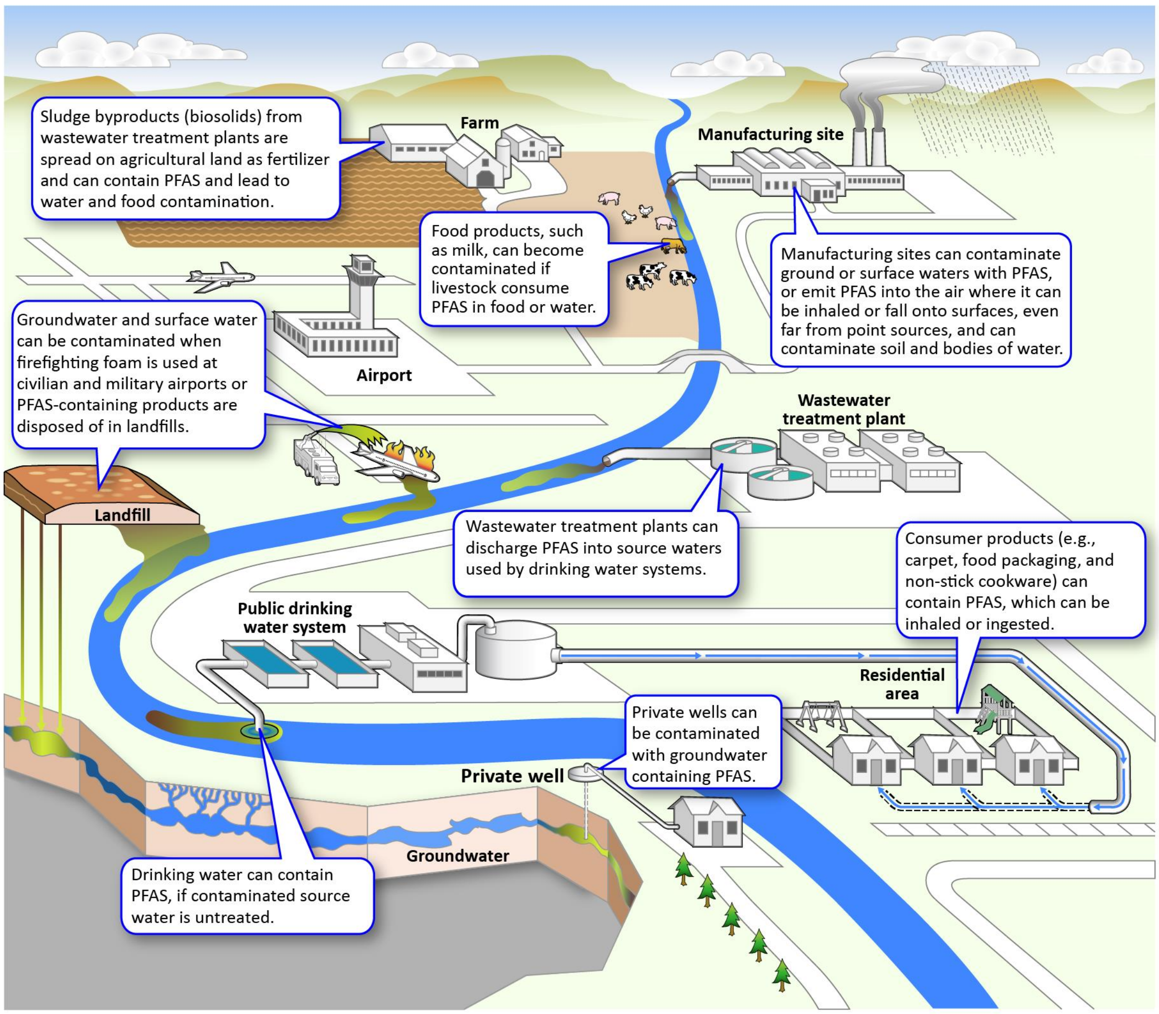
[4]"Long-chain" PFAS have a greater number of carbon atoms linked in a chain; specifically, between 6 to 8 carbon atoms depending on the specific type of PFAS. In contrast, "short-chain" PFAS contain fewer than this number of carbon atoms. Chain length is one of several factors that can affect PFAS behavior in the environment and both long- and short-chain PFAS can result from degradation of more complex PFAS molecules.

[5]The phase-out of PFOS was announced in 2000, and PFOA was phased out as the part of Voluntary Stewardship Program. For more information on the phase-out of these chemicals see https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-and-polyfluoroalkyl-substances-pfas.

[6]Bioaccumulation is defined as the accumulation of a substance and especially a contaminant (such as a pesticide or heavy metal) in a living organism.

a variety of sources (see fig. 1). For example, firefighting foam can seep into groundwater, as can water (i.e., leachate) that drains from landfills where PFAS-containing materials are disposed. PFAS in biosolids—the sludge by-products from wastewater treatment plants that are deposited on agricultural lands as fertilizer—can also run off into surface waters,[7] as can PFAS from the discharge of wastewater effluent. Industrial, manufacturing, and waste incineration facilities can emit PFAS into the air, which may also later affect source waters through contaminated rain.[8]

Figure 1: Per- and polyfluoroalkyl substances (PFAS) can enter the environment and cause human exposure in a variety of ways



Source: GAO. | GAO-22-105088

[7]Interstate Technology and Regulatory Council, *Technical/Regulatory Guidance: Per- and Polyfluoroalkyl Substances* (PFAS) (Washington, D.C: April 2020).

[8]EPA, J. Ryan, *EPA PFAS Air Emission Measurements: Activities and Research*, a paper presented at the EPA Region 9 Laboratory Technical Information Group meeting. June 5, 2019). https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=345762

As noted above, humans may be exposed to PFAS through contaminated water, soil, air, and consumer goods and through the consumption of meat, fish, or dairy products from animals that have been exposed. In general, the risk of adverse human health effects from chemical exposures depends on (1) the level of exposure, which is a combination of how much of the chemical is in the environment and how much contact a person has with it; and (2) toxicity, which is how the chemical affects human health.

Multiple federal agencies conduct research into the health effects of PFAS or fund research conducted by other institutions, such as universities and research centers. Federal agencies involved in this research include EPA; the Department of Defense (DOD); and the Department of Health and Human Services, including the National Institute of Environmental Health Sciences within the National Institutes of Health (NIH), the Agency for Toxic Substances and Disease Registry, and the National Center for Environmental Health within CDC.

1.3 Select agency initiatives and government provisions concerning PFAS

In addition to its research role, EPA also has a role that involves risk assessment and risk management. EPA uses risk assessment to characterize the nature and magnitude of risks to human health for various populations, including children and adults. In a separate process, risk management, the results of risk assessments are integrated with other considerations to reach decisions about risk reduction activities. Such decisions can include restricting the manufacture or use of a chemical.

In 2019, EPA issued its PFAS Action Plan which outlines the tools EPA is developing to, among other things, expand analytical methods to accurately test for additional PFAS in drinking water.[9] In a 2020 update to the plan, EPA noted that it is also working to use (1) a screening level of 40 parts per trillion (ppt) to determine if certain PFAS are present at a site, and (2) EPA's nonenforceable lifetime Drinking Water Health Advisory level of 70 ppt for PFOA and PFOS as the preliminary remediation goal for contaminated groundwater that is a current or potential source of drinking water.[10] In addition, in 2021 EPA issued its PFAS Strategic Roadmap which is the agency's integrated approach to PFAS and is focused on three central directives:

- research – invest in research, development, and innovation to increase understanding of PFAS exposures and toxicities, human health and ecological

[9]EPA, *EPA's Per- and Polyfluoroalkyl Substances (PFAS) Action Plan* (February 2019).

[10]EPA, *EPA PFAS Action Plan Program Update* (February 2020). EPA health advisories, which are nonenforceable and nonregulatory, provide information on contaminants not subject to drinking water regulations, including those that can cause human health effects and are known or anticipated to occur in drinking water. The health advisories are intended for system managers and others with primary responsibility for overseeing water systems. In June 2022, EPA issued interim, updated drinking water health advisories for PFOA and PFOS that replace those EPA issued in 2016. The updated advisory levels, which are based on new science and consider lifetime exposure, indicate that some negative health effects may occur with concentrations of PFOA or PFOS in water that are near zero and below EPA's ability to detect at this time. EPA also issued final health advisories for other PFAS: perfluorobutane sulfonic acid (PFBS) and its potassium salt and for hexafluoropropylene oxide (HFPO) dimer acid and its ammonium salt ("GenX" chemicals).

effects, and effective interventions that incorporate the best available science;

- restrict – pursue a comprehensive approach to proactively prevent PFAS from entering air, land, and water at levels that can adversely impact human health and the environment; and
- remediate – broaden and accelerate the cleanup of PFAS contamination to protect human health and ecological systems.[11]

We also reported in June 2021 that DOD had taken actions under the Comprehensive Environmental Response, Compensation, and Liability Act to address PFAS in drinking water at or near its installations when PFAS amounts exceeded EPA's 2016 Drinking Water Health Advisory level for PFOA and PFOS. The agency also took actions to estimate its future PFAS investigation and cleanup costs, and fund research to develop and identify PFAS-free alternatives to firefighting foam.[12]

In addition to agency initiatives, provisions in some federal statutes authorize states to take their own actions to address PFAS contamination and exposure. For example, states may adopt their own drinking water standards for PFAS even though EPA has not issued any; New Jersey and Michigan are two states that have done so.[13] At a federal level, Congress has passed new statutes and agencies have taken some actions under existing statutes to address the issue of PFAS in the environment (see app. II).

[11] EPA. *PFAS Strategic Roadmap: EPA's Commitments to Action 2021-2024* (October, 2021).

[12] GAO-21-421.

[13] GAO has an ongoing audit examining the extent of PFAS contamination and related state actions; that report will be issued later in 2022.

2 Assessment of PFAS Human Health Risks

Information on the human health effects caused by PFAS exposure can help decision-makers better understand and manage risks from PFAS. Several technologies and methods hold promise for more efficiently assessing human health effects from PFAS. In addition, the potential use of artificial intelligence (AI) with these technologies and methods could more rapidly provide health effects information. However, many of the technologies and methods that could make these assessments more efficient face challenges.

2.1 Technologies and methods to improve the efficiency of PFAS health assessment

For most of the thousands of PFAS, little or no information exists on how potential exposure to these substances may affect human health. Human health effects have primarily been studied for PFOA and PFOS.

Traditional health assessment methods used for PFAS

PFOA, PFOS, and some other PFAS have generally been studied for health effects using two traditional assessment methods:

- **Epidemiological studies** follow human populations over time, and have been used to evaluate possible associations between PFAS exposure and a wide range of adverse health effects. PFAS epidemiological studies have generally focused on highly exposed populations, such as people living or working in highly contaminated places, and the general population. According to an agency report, results from these studies suggest there are many associations between PFAS and adverse health effects, but do not conclusively establish PFAS as the sole cause for the adverse health effects. Some health effects studies show inconsistent or inconclusive findings.

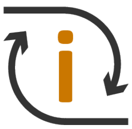
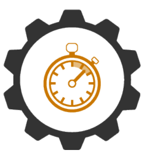
- **Animal studies** in mice and rats have found health effects that include liver toxicity, developmental toxicity, and immune toxicity. However, humans and animals react differently to PFAS, and not all effects observed in animals are relevant for humans. Furthermore, animal testing for the large number of PFAS would require extensive resource in terms of cost, time, and animals.

Source: GAO analysis of agency documents and literature. | GAO-22-105088

More information on human health effects could help government agencies, manufacturers, and individuals better manage the risks posed by PFAS. For example, EPA and state officials could use this information to help them decide where to deploy technologies to remove and dispose of PFAS. (See chapter 4 for further discussion of these treatment technologies.) In addition, PFAS manufacturers could use information on health effects to decide when to discontinue or replace specific PFAS, and individuals and other end users could use it to make decisions about whether to use products containing PFAS.

According to EPA, it would be impossible to expeditiously study the risk that all PFAS pose to human health if they were researched one by one. We identified three categories of technologies and methods that could improve the efficiency of assessing the health effects of PFAS (see table 1). We based these categories on information from federal agencies, experts, stakeholders, and related literature.

Table 1: Categories of technologies and methods for improving efficiency of per- and polyfluoroalkyl substances (PFAS) human health assessments

Technologies and Methods	Description	Benefit(s)
Information integration methods 	Compiles existing PFAS health information from multiple studies into an easily sharable format, such as systematic evidence maps	Provides current PFAS-relevant data that could help researchers expand the scientific understanding of PFAS
High-throughput technologies and methods 	Rapidly evaluates a large number of PFAS for biological responses, such as possible adverse health effects.	Can be used to prioritize PFAS with potential health effects on human health for additional testing
Predictive methods 	Uses models to predict health effects of multiple PFAS based on structural similarities, such as quantitative structure-activity relationships (QSAR)	Better understand PFAS with no toxicity data

Source: GAO analysis of information from federal agencies, experts, stakeholders, and related literature. | GAO-22-105088

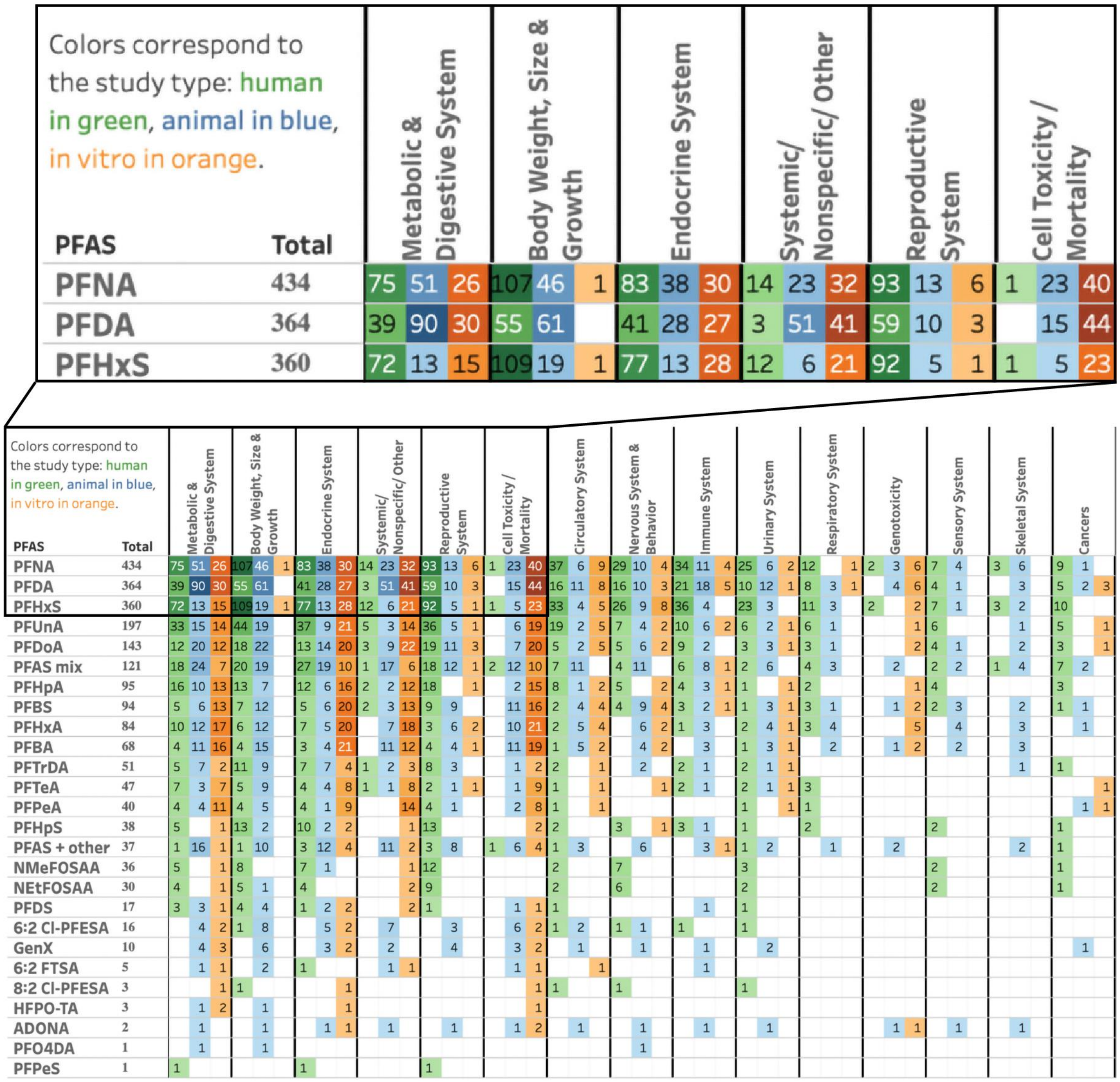
Information integration involves compiling existing PFAS health information from multiple studies into an easily sharable format. One way that EPA is doing this is by compiling scientific literature on PFAS toxicity into existing chemical databases to support PFAS research. By doing this, EPA ensures the databases contain comprehensive and current PFAS-relevant data that could help researchers expand the scientific understanding of PFAS and help decision-makers better manage risk from PFAS.

Systematic evidence maps are another format for integrating existing information. In this method, results from health effects studies are coded to represent different categories and organized into a searchable database. The coding makes these databases different from those described above, and these maps allows researchers to quickly identify trends, data gaps, and evidence clusters. For example, a systematic evidence map known as the PFAS-Tox Database categorizes and organizes over a thousand studies of 29 PFAS by the type of health effect and parts of the body where they occur (see fig. 2).[14] According to experts who maintain the database, as of April 2022, it has been accessed more than 35,000 times, and researchers are using it to conduct systematic reviews on PFAS exposure and specific health outcomes. EPA is also using a similar approach to identify and summarize evidence from animal studies and human epidemiological studies for approximately 9,000 PFAS.[15]

[14]These studies included 505 studies of human health effects, 385 animal studies, and 220 in vitro studies. The figure reproduces a portion of the PFAS-Tox Database published on Mar 23, 2022 online at the nongovernmental organizations website: https://pfastoxdatabase.org/.

[15]The list of 9,000 PFAS substances and structures includes most of the chemicals in EPA's CompTox chemicals dashboard. https://comptox.epa.gov/dashboard/chemical_lists/PFASSTRUCT

Figure 2: The PFAS Tox-Database is a systemic evidence map on human health effects from per- and polyfluoroalkyl substances (PFAS)

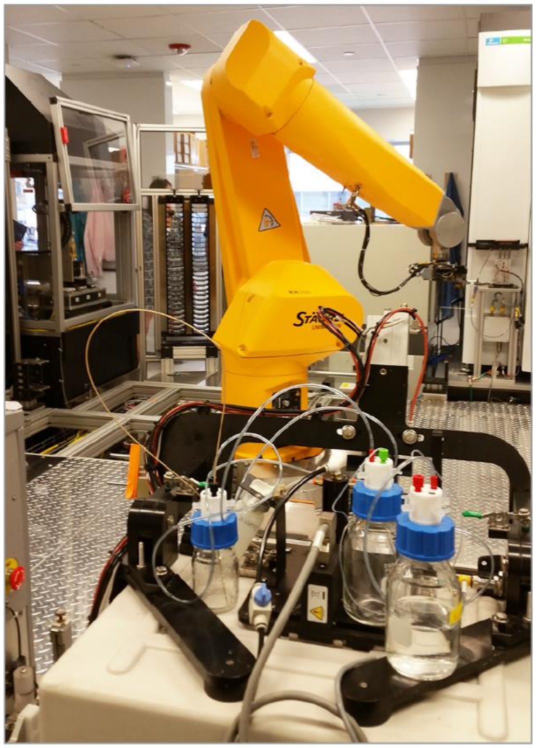


Source: Social Science Environmental Health Research Institute. | GAO-22-105088

Note: The numbers in the heat map indicate the number of studies, not the number of significant effects.

High-throughput technologies and methods rapidly evaluate large numbers of chemicals for biological responses. Researchers are using these assays to examine the effects of PFAS on molecular and cellular functions. EPA is currently using these methods to quickly provide an initial understanding of the possible adverse health effects from PFAS. For one such effort, EPA has completed high-throughput toxicity testing on approximately 150 different PFAS. Figure 3 shows a robotic arm that performs high-throughput screening of chemicals at NIH. EPA officials told us the agency may use the results to identify PFAS that show a potential effect on human health and prioritize them for further testing using more costly and time-consuming methods.

Figure 3: High throughput screening uses technology, such as this robotic arm, to quickly assess multiple chemicals



Source: GAO. | GAO-22-105088

Predictive methods—such as grouping and quantitative structure-activity relationship (QSAR) models—are used to assess the likely health effects of many PFAS at once, since structurally similar chemicals are more likely to have similar health effects.

Grouping is a method that assigns PFAS into categories based on structural or other similarities, such as the elements in the molecule and their arrangement. In October 2021, EPA systematically grouped 6,504 PFAS into 70 final categories based on their structures and physical-chemical properties, and then selected representative PFAS from the categories for further studies.[16] According to EPA officials, the agency will use the results to more rapidly evaluate the toxicity and risks associated with this large class of chemicals.

QSAR models predict health effects using two data sets for the same set of PFAS chemicals: one on the chemical structures and one on the response of living tissues to exposure, known as activity. These models analyze these data sets to relate PFAS structure to activity. However, data sets for PFAS remain limited. Many of the QSAR studies that we reviewed used molecular simulation, a computation method that simulates the interaction of chemicals within molecules, to build artificial data sets for statistical analysis. Researchers have used QSAR modeling to estimate the toxicity of multiple PFAS. For example, in one study, researchers used QSAR modeling to predict the bioactivity of 3,486 PFAS.[17]

Information gained through the assessment of PFAS with these technologies and methods—information integration, high-throughput technologies and methods, and predictive methods—can be used to prioritize PFAS for further research. It can also fill gaps in information about the likely health effects of particular PFAS, which may help decision-makers better manage risk. In addition, using these technologies and methods in conjunction can further improve the assessment of PFAS health risks. For example, the results of the assessment of PFAS by high-

[16] EPA, *National PFAS Testing Strategy: Identification of Candidate Per- and Poly-fluoroalkyl Substances (PFAS) for Testing*, (Washington, D.C.: October 1, 2021).

[17] Weixiao Cheng and Carla Ng, “Using Machine Learning to Classify Bioactivity for 3,486 Per- and Polyfluoroalkyl Substances (PFASs) from the OECD list,” *Environmental Science Technology*, 53, (2019), 13970-13980.

throughput methods and information integration can be used as input for predictive methods.

2.2 Application of AI/ML for more efficient assessments

Artificial intelligence could further improve the efficiency of PFAS assessments for health effects when used in combination with the technologies and methods described above.[18] The use of AI in assessing PFAS is limited and very early in development and requires more research and development before it can be applied to PFAS assessments, according to federal agencies.

Machine learning (ML)—along with other computing technology—could make it easier to collect, organize, and assess large amounts of information. If applied, according to EPA, ML could be used to search for, screen, and collect data from relevant toxicological and epidemiological studies, thus removing barriers associated with manually evaluating the large volume of data on PFAS. For example, EPA officials told us that they routinely use ML to screen studies for inclusion in systematic evidence maps.

Another promising application is with predictive methods. For example, ML algorithms could make QSAR models more efficient for assessing PFAS using large data sets. According to federal agency officials, the development of QSAR modeling using PFAS-relevant training data would enable toxicology researchers to better predict the environmental fate, behavior, and health effects of PFAS. These technologies have been combined in a study, with limited results. For example, a PFAS study using QSAR also used ML to predict the bioactivity of 3,486 PFAS.[19] However, the model predicted only whether there was some kind of bioactivity, not health effects intensity or outcomes based on level of exposure.

2.3 Challenges to technologies and methods for PFAS health effects assessment

We identified three key challenges that affect the development and use of many of the technologies and methods that could make the assessment of human health effects from PFAS more efficient.

First, these approaches provide limited information on health outcomes. For example, according to federal agencies, the technologies do not reliably predict complex health outcomes, such as developmental and repeated exposure toxicity. Instead, EPA uses information gained through these technologies and methods to identify information gaps and prioritize PFAS for

[18]AI includes at least three types of technology. With expert (or rules-based) systems, a computer produces outputs consistent with its programming, which is based on expert knowledge or criteria. With machine learning, the system instead begins with data and infers rules or decision procedures that predict specified outcomes. General AI systems, which are not yet developed, would be capable of contextual sophistication, abstraction, and explanation and could explain to users the reasoning behind their decisions.

[19]Cheng and Ng, "Using Machine Learning to Classify Bioactivity for 3486 PFAS," 13970.

further research with more costly and time-consuming methods, such as animal testing.

Second, the diversity of PFAS and lack of understanding of their fate, transformation, and behavior in humans creates a barrier to the use of predictive technologies and methods. According to EPA, scientists have an incomplete understanding of chemical structure and behavior once a molecule enters an organism. In addition, experts from one organization noted that toxicity may differ across body tissues and among different PFAS, making it difficult to make structure-based predictions. According to experts from the same organization, this challenge is exacerbated by the large number of PFAS that have not yet been studied, and the potential for exposure to mixtures of PFAS in the environment.

Finally, according to experts, researchers lack sufficient reliable data for use with ML in the assessment of most PFAS. A reliable data set that includes physical or biological characteristics of PFAS must be available to train ML models to predict the health effects of similar PFAS. Without such data, the utility of ML is limited. For example, we found that the results of one study that combined ML with QSAR were limited to predicting biological activity when a human is exposed to PFAS.[20] According to the study, expanding the data set to cover a broader range of molecular properties in the future would lead to a better understanding of additional critical factors related to PFAS.

Machine learning to assess alternatives to PFAS

One option for addressing PFAS health risk is to replace PFAS in products or processes with safer alternatives. The Department of Defense's Strategic Environmental Research and Development Program and Environmental Security Technology Certification Program are funding research to develop alternatives to PFAS-containing firefighting foam by 2023. Use of such foams has led to the known or suspected release of PFAS at or near hundreds of installations across the U.S., including release into drinking water. In one project, researchers are using machine learning to more rapidly search for alternatives. More specifically, researchers are using experiments at the molecular level to discover what makes PFAS-containing firefighting foam so effective, and then building machine learning models that predict alternatives with similar properties. Figure 4 shows the use of firefighting foam.

Figure 4: Firefighters using chemical foam coming through a home

Source: mushegovdiva/stock.adobe.com. | GAO-22-105088

Source: GAO analysis of agency documents and literature.| GAO-22-105088

[20]Cheng and Ng, "Using Machine Learning to Classify Bioactivity for 3486 PFAS," 13970.

3 PFAS Detection

3.1 Current technologies for PFAS detection fall into three categories

The current technologies for PFAS detection can be classified as targeted, non-targeted, and total fluorine methods (see table 2). Targeted methods only detect PFAS that the researcher selects, or "targets," for analysis. Such methods require a reliable sample, known as an analytical standard, of the targeted PFAS to definitively identify and quantify it; however, researchers lack such standards for the vast majority of PFAS. To detect PFAS without analytical standards, researchers have developed non-targeted and total fluorine methods. These methods enable them to discover and characterize unknown PFAS to a limited extent or estimate the total amount of PFAS. However, most of these methods are still in development or not widely available and can be costly.

Because current technology cannot confirm the identity of PFAS without an analytical standard, EPA is limited in its ability to respond to potential PFAS contamination. For example, EPA cannot reliably determine the extent or risks of PFAS contamination at a given site. In addition, the lack of available standards makes it difficult to develop new detection methods—in particular, for media other than drinking water, such as soil. EPA officials told us the lack of available standards is a primary factor limiting development of new detection methods for PFAS.

Table 2: Current detection technologies for per- and polyfluoroalkyl substances (PFAS)

Technology	Environmental media	Advantages	Limitations
Targeted methods	Water (potable and non-potable), solids, soil, air, leachate	Sensitive - can detect some PFAS down to-0.1 parts per trillion (ppt) EPA methods exist for this technology.	Method can only detect specific PFAS targeted for analysis and for which a standard is available.
Non-targeted methods	Water (potable and non-potable), solids, soil, air, leachate	Can screen for PFAS broadly, discover new PFAS without need for analytical standards.	Cannot measure amount of newly discovered PFAS without analytical standard. No EPA methods exist.
Total fluorine methods	Most methods designed for detection in water (potable and non-potable), some applied to soil	Can quantify PFAS at high concentrations (~1,000 ppt) that would be unquantifiable by other methods.	Total fluorine methods are not standardized or multilaboratory-validated as EPA methods. Most are not widely available and some are more costly.

Source: GAO analysis of agency documents. | GAO-22-105088

3.2 Targeted methods can detect about 1 percent of PFAS at low levels

Targeted methods can reliably detect PFAS at low concentrations, in some instances less than 1 ppt, but are limited in their application. These methods can only be used to detect about 1 percent of PFAS—those for which manufacturers or commercial suppliers have provided analytical standards to EPA and EPA has finalized standardized detection methods.[21] Furthermore, these EPA finalized targeted methods only apply to water, not to soil, air, or other media.[22]

EPA currently has two finalized, published methods for detection of PFAS in drinking water, which together can detect 29 unique PFAS. EPA has also published one method for other water (e.g., wastewater, untreated surface water, groundwater), which can detect 24 PFAS. These three EPA methods are:

- Method 537.1, which can detect and quantify 18 targeted PFAS compounds in drinking water, some at concentrations of less than 1 ppt
- Method 533, which is better able to detect short-chain PFAS compounds in drinking water, and can detect and quantify 25 targeted PFAS, including most of those detectable using Method 537.1
- Method 8327, which can detect and quantify 24 targeted PFAS in groundwater, surface water, and wastewater

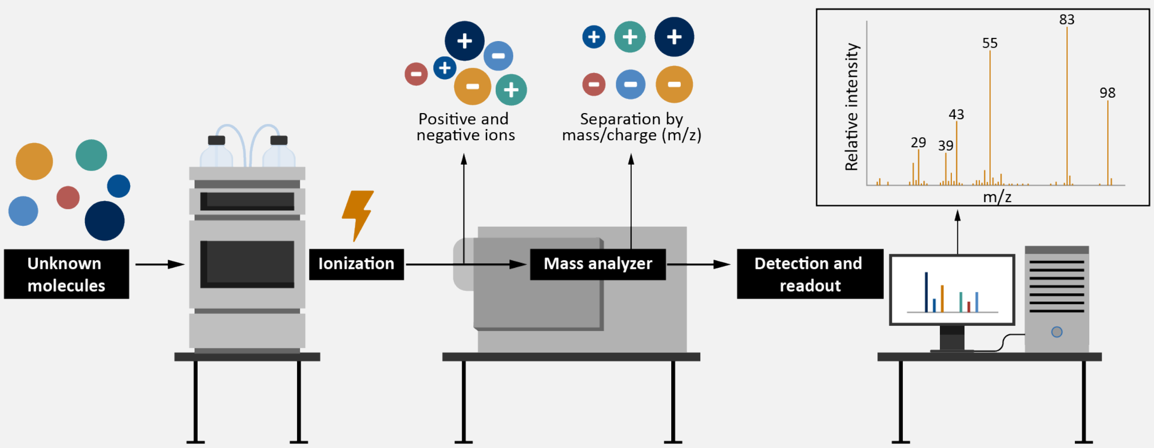
[21]EPA methods can be finalized, published methods, research methods, or developmental methods. Finalized, published methods have been validated by multiple laboratories and finalized for use by researchers across the country. The only finalized published EPA methods available now for PFAS are targeted methods. For this report, we use "EPA methods" to refer to EPA methods that have been finalized for use.

[22]EPA has published one draft method for air, *Other Test Method (OTM) 45* and another for wastewater, surface water groundwater, soil, biosolids, sediment, landfill leachate, and fish tissue, draft EPA Method 1633. According to EPA officials, the agency currently has no timetable for validating OTM-45 and Method 1633 is undergoing a multi-laboratory validation study.

Mass spectrometry

The existing methods for PFAS detection typically require a tool called a mass spectrometer. Many scientific disciplines use mass spectrometers and they are common in industrial, commercial, and academic laboratories. They ionize (charge) unknown molecules in a sample and then use magnetic or electric fields (or both) to accelerate the ions, typically in a vacuum. By measuring how a molecule travels after being accelerated, the mass spectrometer can precisely measure its mass-to-charge ratio (m/z). This measurement allows researchers to identify substances such as PFAS and quantify their concentration in a given sample (see fig. 5). Methods that use mass spectrometers can reliably detect and quantify certain PFAS at low concentrations—less than 10 parts per trillion (ppt) and in some cases below 1 ppt.

Figure 5: Mass spectrometry technology



Source: GAO analysis of peer reviewed journal articles. | GAO-22-105088

Source: GAO analysis of peer reviewed journal articles| GAO-22-105088

Under EPA's third Unregulated Contaminant Monitoring Rule (UCMR3) required 4,864 public water systems used a targeted method to test for six specific PFAS between 2013 and 2015. The monitoring showed that 63 of the systems, or 1.3 percent, exceeded EPA's Drinking Water Health Advisory for at least one of two PFAS (PFOA and PFOS, separately or combined).[23] The fifth UCMR (UCMR5) will require public water systems to measure PFAS in drinking water from 2023 to 2025 and is anticipated to include the 29 PFAS listed in EPA Methods 537.1 and 533.

These targeted methods can be highly sensitive and accurate, but difficult to interpret in some cases. For example, the very low limits of detection required by some state PFAS guidelines may make it difficult to rule out trace contamination from sampling containers or the laboratory equipment[24], which can also contain PFAS, as sources of PFAS measured in a sample. Furthermore, some PFAS appear to change over time into other PFAS via natural

[23]At the time of UCMR3, EPA had only established a provisional Drinking Water Health Advisory level for PFOA and PFOS, two of the most studied PFAS at the time.

[24]For example, according to the Environmental Council of States, Illinois has a guideline level for PFOA in groundwater of 2 ppt, using EPA method 8327. However, according to EPA's multi-laboratory validation study for method 8327, the lowest reliable quantification level for PFOA concentration with this method is 10-20 ppt.

processes, which could prevent accurate detection via targeted methods.

3.3 Non-targeted methods can detect but not quantify unknown PFAS

Non-targeted methods screen broadly for the presence of suspected PFAS and can detect unknown PFAS in a sample. These methods can be particularly useful for detecting environmental contamination by PFAS for which no analytical standard is available.

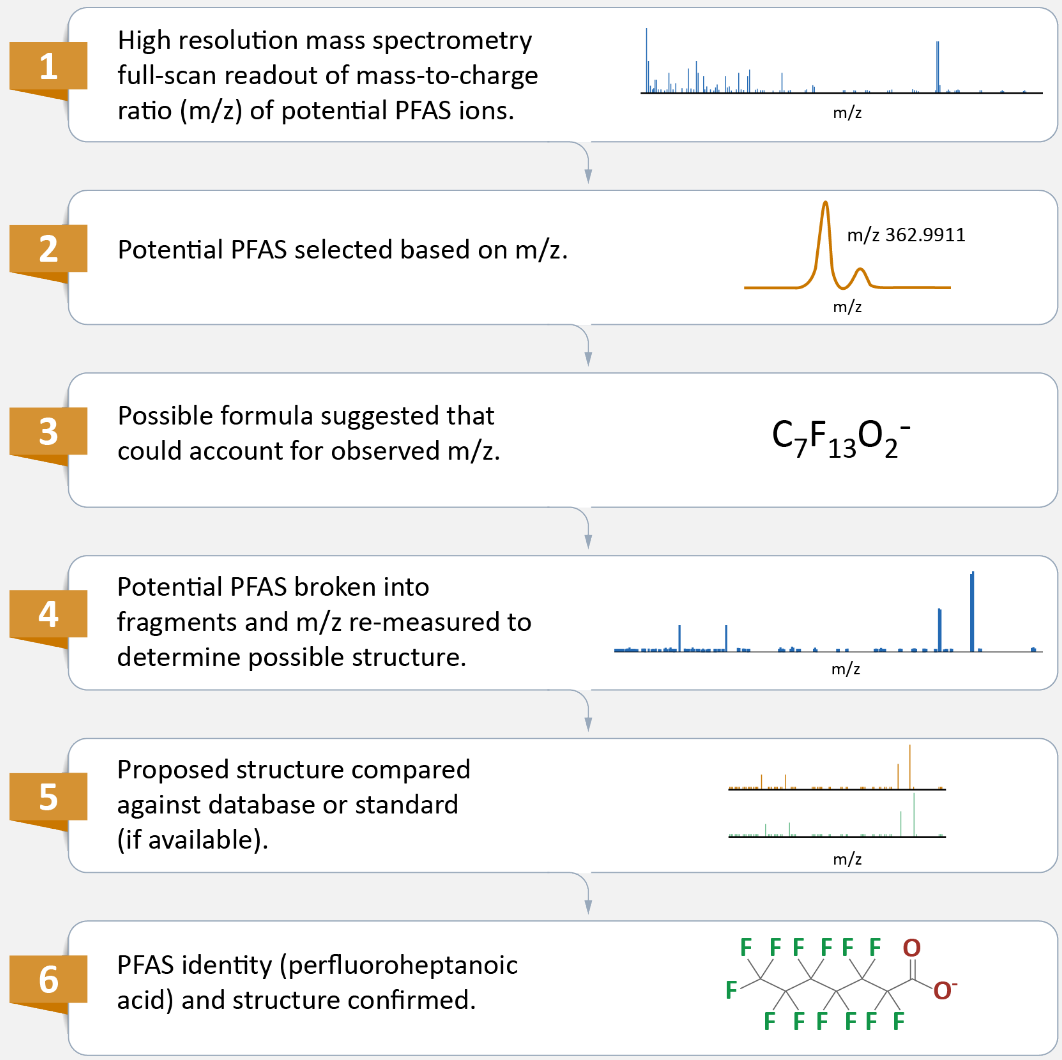
Instead of standards, these methods use very accurate measurements of mass to narrow down the possible molecular structures and formulas for an unknown molecule and use fragmentation to assign possible molecular structures. They then compare these measurements to large collections of measurements made by other researchers or predicted values from computer simulations to further narrow down the formulas and structures. The easiest application of non-targeted methods were limited to screening for suspected pollutants ("known unknowns"). However, the necessary data were only available for a few compounds, and the results required expert interpretation.

More recently, researchers have capitalized on improvements to mass analyzers and their integration into mass spectrometer technology to develop high resolution mass spectrometry (HRMS). This non-targeted method can detect a wider range of PFAS than earlier methods (see fig. 6). It is a promising method for PFAS detection because it combines more accurate measurement of mass with improved ability to predict molecular formulas (see text box). These advantages enable HRMS to speed up the confirmation of a molecule's structure and formula by greatly reducing the number of potential formulas that need to be considered. Researchers have used HRMS to discover 750 new or unexpected PFAS and to better understand the extent and potential sources of PFAS contamination.

High resolution mass spectrometry (HRMS)

A typical environmental sample contains many different kinds of molecules. In HRMS, as shown in figure 6 below, each chemically distinct molecule generates a “peak” on the graph that a mass spectrometer produces as its output. In HRMS, this peak can be measured with much greater accuracy by very sensitive mass analyzers and fragmentation—which involves breaking the unknown molecule apart with high-energy particles to see what other molecules it is made of. This procedure can tentatively identify new PFAS, but their presence still needs to be confirmed by traditional methods using a sample, or analytical standard, of the suspected PFAS.

Figure 6: Steps in the high-resolution mass (HRMS) spectrometry process



Source: GAO analysis of High Resolution Mass Spectrometry (HRMS) publications. | GAO-22-105088

Source: GAO analysis of published literature.| GAO-22-105088

EPA researchers have used non-targeted HRMS screening and sampling near known sources of PFAS, such as manufacturing facilities, to detect potential contamination by known and previously unknown PFAS.

For example, EPA researchers used HRMS in Alabama to discover 19 PFAS compounds downstream from facilities that may be emitting them as a by-product of their manufacturing process for another chemical.[25] In New Jersey, EPA researchers used non-targeted HRMS screening to identify and map PFAS compounds in soil that suggested airborne transport from known PFAS manufacturing facilities.[26]

While HRMS has been proven to be a useful tool for PFAS discovery, there are some limitations to the approach. In particular, an analytical standard is still required to confirm identification of any newly discovered PFAS. Without an analytical standard at some point in the analysis, HRMS also cannot reliably determine how much of the new PFAS is present in a sample, and thus, in the environment.

Another limitation of HRMS is a lack of standardization. There is no finalized EPA method for using HRMS, and researchers have developed a variety of approaches to using HRMS, which can make them difficult to compare and interpret to gain a broader picture of PFAS contamination. According to agency officials, researchers using non-targeted analysis like HRMS must also possess substantial experience interpreting mass spectrometry data and have access to mass spectrometry libraries to correctly identify PFAS.

3.4 Some methods can estimate the extent of PFAS in a sample but not identify them

Fluorine is a component of all PFAS, so quantifying fluorine is a way to estimate PFAS concentrations without needing to identify specific compounds (see table 3). However, there are other sources of fluorine in the environment in addition to PFAS, such as some pesticides and pharmaceuticals, and these methods vary in their effectiveness depending on the forms or amounts of fluorine that are present, so they are limited to estimating potential PFAS concentrations. After further development, these methods might be useful in determining the areas of a contaminated site with the highest concentrations of PFAS or estimating how much PFAS a manufacturer is releasing.

[25] S. Newton, R. McMahen, J.A. Stoeckel, M. Chislock, A. Lindstrom, and M. Strynar, "Novel Polyfluorinated Compounds Identified Using High Resolution Mass Spectrometry Downstream of Manufacturing Facilities near Decatur, Alabama," *Environmental Science and Technology*, vol. 51 (2017): 1544−1552.

[26] J.W. Washington, C.G. Rosal, J.P. McCord, M.J. Strynar, A.B. Lindstrom, E.L. Bergman, S.M. Goodrow, H.K. Tadesse, A.N. Pilant, B.J. Washington, M.J. Davis, B.G. Stuart, and T.M. Jenkins, "Nontargeted Mass-Spectral Detection of Chloroperfluoropolyether Carboxylates in New Jersey Soils," *Science,* vol. 5, no. 368 (2020): 1103–1107.

Table 3: Total fluorine methods for per- and polyfluoroalkyl substances (PFAS)

Technology	Description	Uses	Limitations	Development status
Combustion ion chromatography	PFAS are removed from a sample onto a carbon filter (adsorbed) and then burned to release the adsorbed organic fluorine, which is measured via ion chromatography.	Under investigation as a rapid screening tool for the presence or absence of PFAS in environmental samples, such as soils, seawater, freshwater, and sediments.	May only detect high levels of PFAS. Cannot PFAS apart from other organic fluorine.	The Environmental Protection Agency (EPA) has developed a draft method that was published in April 2022.
Total oxidizable precursor (TOP)	PFAS that are missed by current methods are transformed into PFAS that can be measured by current methods.	Has been applied at wastewater treatment plants and PFAS-containing firefighting foam sites. It confirmed that EPA methods miss 30% or more of PFAS.	Cannot tell which PFAS precursors are present. Only available from some labs.	Six states are using TOP to screen for PFAS in water, soil, firefighting foam, etc. An EPA research method exists but is not being developed for public use.
Particle-induced gamma-ray emission	A high-power proton beam irradiates a surface, releasing gamma radiation that can indicate the amount of total fluorine present on a surface.	Under investigation as a rapid screening tool for PFAS in environmental samples and products.	Technique has only been widely demonstrated for solid materials, not for soil or water samples.	Method has not been standardized, and is still in early development.

Source: GAO analysis of agency and industry documents. | GAO-22-105088

Combustion ion chromatography is the most common method for measuring total fluorine in a sample.[27] In this method, PFAS is removed from a sample onto activated carbon, which is burned to release organic fluorine. The fluorine is then measured via ion chromatography.[28] An advantage of this method is that it does not require costly or specialized equipment.

Some researchers have reported that measuring total fluorine via combustion ion chromatography can only detect high levels of PFAS. This method is therefore being investigated as a rapid screening tool for the presence or absence of PFAS in environmental samples, rather than as a method to fully assess contamination levels.

[27] Ion chromatography is a form of liquid chromatography. It measures concentrations of ions by separating them based on their interaction with a resin. Ions separate differently depending on their type and size. Ion chromatographs are able to measure concentrations of major anions, such as fluoride, in the parts-per-billion (ppb) range.

[28] Organofluorines, or organic fluorine, refers to organic molecules with fluorine bonded to carbon atoms. PFAS are organofluorines.

Combustion ion chromatography has been applied to a variety of media, including seawater, freshwater, sediments, and soils. EPA began researching this method for total organic fluorine analysis in 2020, and a draft method was published for testing and review in April 2022.[29] The draft method we reviewed noted that combustion ion chromatography was useful for its ability to broadly sample for PFAS, but has the potential to give incorrect estimates. For example, it cannot distinguish fluorine-containing pharmaceuticals that do not meet the definition of PFAS, which can lead to an overestimate of total PFAS concentration. EPA notes that its draft method for measuring total organic fluorine via combustion ion chromatography also is less accurate at detecting short-chain PFAS than long-chain versions.

The **total oxidizable precursor (TOP) assay** is a detection method that estimates the total concentration of some PFAS (called "precursors") in a sample. It does this by transforming PFAS precursors through a process called oxidation into other PFAS that targeted methods can measure. The TOP assay method can be fairly sensitive, detecting the transformed PFAS at concentrations of 0.1 to 1 ppt. However, at most, only about 20 percent of PFAS can be detected using this method.

Using TOP, researchers have found that traditional, targeted methods of detection fail to routinely quantify 33 to 63 percent of PFAS in wastewater treatment plants[30]. The TOP methodology has also been applied to sites contaminated by PFAS-containing firefighting foam. Researchers using TOP at these sites estimated that targeted methods are only detecting an estimated 30 to 50 percent of the PFAS precursors in a sample. While it is a useful approach for confirming the presence of PFAS compounds undetectable by current EPA methods, the TOP assay does not distinguish among different PFAS that can break down into the same PFAS through natural processes. This can limit the utility of the TOP assay and its ability to characterize specific PFAS that are present in a sample. As of April 14, 2022, EPA does not plan to develop TOP into a finalized EPA method. However, TOP assays are conducted by some commercial laboratories.

There are also several emerging technologies for total fluorine measurement. For example, **particle-induced gamma-ray emission spectroscopy**, which is a long-established technology for analysis of solid materials, has the potential to be a high-throughput (20+ samples per hour) and sensitive technique for PFAS detection. This method is still in early development; it has not been refined for use with environmental samples (water, soil, or air), and there is no reliable organic fluorine extraction method that would enable this method to distinguish between inorganic fluorine (unlikely to be

[29] EPA Draft Method 1621 is a screening method for the determination of adsorbable organic fluorine (AOF) in aqueous media by combustion ion chromatography. EPA began a multi-laboratory validation study of the procedure in 2022.

[30] E.F. Houtz, R. Sutton, J.S. Park, and M. Sedlak. "Poly- and perfluoroalkyl substances in wastewater: significance of unknown precursors, manufacturing shifts, and likely AFFF impacts." *Water Research,* vol 95, (2016): 142–149.

PFAS) and organic fluorine (more likely to be PFAS).

3.5 Challenges affecting PFAS detection

We identified the following challenges to further developing and applying PFAS detection technologies and methods:

Cost. Cost of sample analysis is a key challenge, according to academic experts we spoke with and agencies we surveyed. One academic expert cited a contract laboratory's cost of up to $500 per sample, and instrumentation for mass spectrometry can initially cost over $500,000 to acquire and set up, plus over $250,000 a year to maintain and operate. These costs may be prohibitive for private well owners and smaller utilities.

Varying guidance. According to the Environmental Council of the States, PFAS detection policies and regulations vary by state and are uncertain at the federal level.[31] For example, states differ in the specific PFAS they regulate and the methods they prescribe for PFAS detection. This uncertainty among states may inhibit efforts to decrease the cost of PFAS detection through standardization and validation of methods.

Limited applicability. The only currently finalized EPA methods for PFAS detection that have been validated by multiple laboratories are for detection in water or for removing and measuring solids containing PFAS from water. EPA is testing and refining methods for other media, but agencies and researchers are currently unable to comprehensively detect, trace, and assess PFAS contamination in the environment.

Lack of analytical standards and methods. Current technologies cannot detect and quantify most PFAS because reliable analytical standards are not available. According to researchers, fewer than 100 analytical standards exist for the more than 4,700 known PFAS.[32] Finalized EPA methods, at most, can detect and quantify only 50 of these PFAS (i.e., approximately 1 percent). And these technologies cannot confirm the identity of unknown PFAS discovered in certain environments because of a lack of methods.

Agency officials we spoke with cited the lack of available standards as the greatest challenge to PFAS detection. It also limits academic researchers' efforts to develop new and potentially more efficient and accurate methods for PFAS detection because standards are required to confirm the accuracy of those methods.

[31] S.G. Longsworth, "Processes & Considerations for Setting State PFAS Standards," *Environmental Council of the States White Paper*, (April 29, 2021). https://www.ecos.org/wp-content/uploads/2021/04/Updated-Standards-White-Paper-April-2021.pdf

[32] C.A. McDonough, J.L. Guelfo, and C.P. Higgins, "Measuring Total PFASs in Water: The Tradeoff Between Selectivity and Inclusivity," *Current Opinions: Environmental Science and Health*, vol. 7 (2019): 13-18.

4 PFAS Treatment

Current PFAS treatment technologies can be broken down into three categories, depending on whether they focus on (1) removing PFAS from water, soil, or air, (2) disposing of PFAS-contaminated material, or (3) destroying PFAS-contaminated material.[33] To date, PFAS treatment technologies have been used at full scale for the removal of PFAS from water, and these vary in effectiveness.[34] Disposal technologies also vary in effectiveness, and disposal sites without proper controls can themselves become sources of contamination. Destruction would be a permanent solution, but no destruction method has yet been proven fully effective for all known PFAS, according to experts, published research, and agency materials. In addition, several challenges hinder PFAS treatment, including cost, lack of guidance, and lack of proven methods.

4.1 Current removal technologies are effective for some PFAS

Current removal technologies can remove up to 90 percent or more of 30 different PFAS from water, creating PFAS-contaminated residual materials as a by-product (see 4.2 and 4.3 below for disposal and destruction technologies relevant to these residual materials). The currently available technologies for removal of PFAS from water vary in effectiveness, but all can remove up to 90 percent or more of certain PFAS (see table 4), which are easier to remove from water than other PFAS.[35] These technologies are available and currently being used for industrial wastewater and by federal agencies, some municipal drinking water treatment plants and individual households.

[33]For this report, we use the term “treatment” to include technologies related to the removal, destruction, and disposal of PFAS.

[34]For this report, we use the term “full scale” to refer to demonstration of effectiveness at a commercial facility operating under normal conditions. This is distinct from “research,” “lab,” “bench,” or “pilot-scale” studies, which are done under more experimental conditions, to determine the conditions needed for full-scale application.

[35]Deciding which technology is best suited will likely depend on the type of PFAS present, local water quality, and local treatment goals. A number of factors contribute to the removal effectiveness of a given technology, including the concentration of PFAS in the water, presence of other contaminants, and pH level, among others.

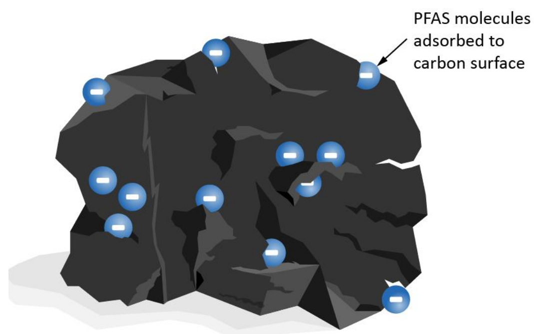
Table 4: Technologies to remove per- and polyfluoroalkyl substances (PFAS) from water

Technology	Description	Uses and limitations
Granular activated carbon (GAC) filtration	Filters with a large, porous surface area attract and bind a wide range of contaminants, including PFAS.	Suitable for public drinking water plants and households, particularly when PFAS levels are relatively low. Can allow short-chain PFAS to evade removal, especially if filters are not replaced often enough. Filters are relatively inexpensive.
Ion exchange resin	These resins use the charges of PFAS molecules to attract them to oppositely charged sites.	More flexible than GAC – can be adjusted to remove specific PFAS more efficiently. Can treat a larger volume of water before the resin needs to be replaced. Requires less energy and space than the other methods.
Reverse osmosis and nanofiltration membrane	High pressure forces water through very small openings in the membrane, which prevents PFAS from passing through.	Suitable for drinking water plants and households, particularly when PFAS concentrations are high. About 10 to 20 percent of the water being treated becomes contaminant-enriched concentrate, which must be disposed of or otherwise treated. Requires pretreatment to reduce buildup that blocks the membrane. Relatively high cost due to significant power needed for high pressure.

Source: GAO analysis of agency and industry documents. | GAO-22-105088

Granular activated carbon (GAC) filtration is the least costly technology to purchase, and while it is effective for long-chain PFAS, it is the least effective technology at removing short-chain PFAS (see fig. 7). This is because, while GAC filters attract and bind a wide range of contaminants to their large surface area, the short-chain PFAS do not adhere to GAC filters as readily as long-chain PFAS and can potentially remain in the drinking water even after GAC treatment. Since short-chain PFAS may be present in almost a hundred drinking water treatment plants that have reported PFAS present in their source water, this can be a significant challenge.[36]

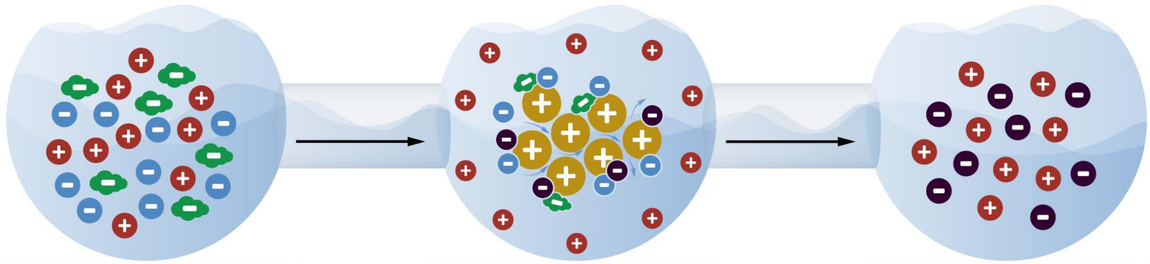
Figure 7: How granular activated carbon (GAC) removes PFAS



Source: GAO. | GAO-22-105088

[36]EPA UCMR3 Data Summary, January 2017. https://www.epa.gov/sites/default/files/2017-02/documents/ucmr3-data-summaryjanuary- 2017.pdf

Figure 8: How ion exchange removes PFAS



Source water containing a mixture of positively and negatively charged contaminant molecules enters the resin bed area.

As water is passed through the resin bed, oppositely charged contaminant molecules bind to the charged resin and chloride ions are released.

Treated water exits the resin bed with positively charged contaminants and chloride ions.

Resin | Positively charged contaminants | Negatively charged PFAS | Chloride ions | Other negatively charged contaminants

Source: GAO analysis of American Water Works Association information. | GAO-22-105088

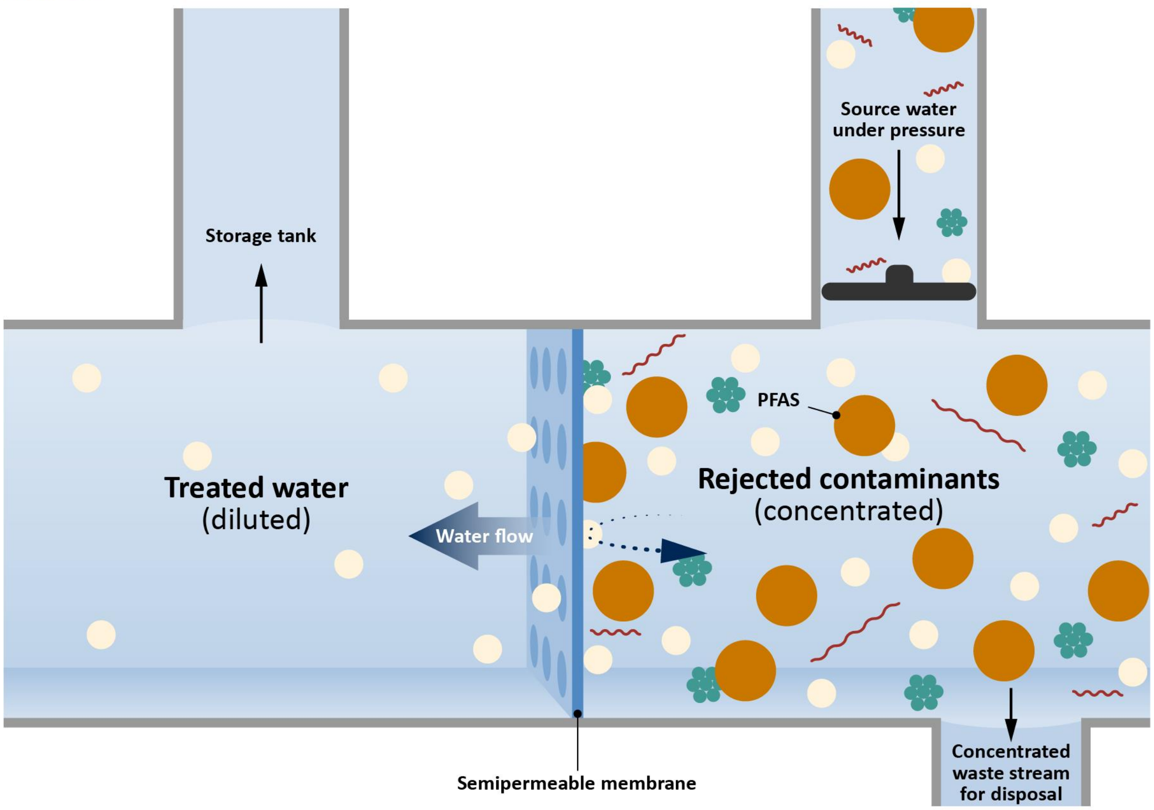
Ion exchange resin technologies can be generally more effective for PFAS removal than GAC. In ion exchange, source water passes through a resin that acts as a filter to remove undesirable ions (i.e., charged particles), such as negatively charged PFAS molecules, by 'exchanging' them for less harmful ions such as chloride ions (see fig. 8.) Like GAC, the resin has a large surface area that binds contaminants. It also uses an electric charge to attract PFAS molecules. Because of this combination of mechanisms, it can remove up to four times as much PFAS as GAC. Although harder to recycle than GAC and more expensive to purchase, ion exchange may use less energy and space (depending on how it is designed and local water quality), require less maintenance, and be more cost-effective at higher PFAS concentrations.

Reverse osmosis (RO) technologies can be quite effective for PFAS removal, but also more expensive. According to agency documents, PFAS removal efficiency for these membrane separation technologies is 80 percent to over 99 percent, regardless of chain length. RO achieves this efficiency by filtering water through a membrane with a very small pore size, which filters out even the smallest PFAS molecules (see fig. 9). However, RO also requires significant power to force water through the pores, thus making it energy intensive, and it can lead to a significant loss of the source water as contaminant-enriched backwash is rejected by the membrane, which can be a problem in locations where source water is scarce. For these reasons, RO technology may not be cost effective for PFAS removal at a water treatment plant—unless the goal is to reduce PFAS to very low levels, or if PFAS concentrations are so high that using GAC or ion exchange filters is unsustainable.

Household use of these technologies can also be effective. In a study of 73 homes in North Carolina with elevated levels of PFAS in their water supply, household-scale RO filters removed nearly all PFAS targeted in the study, while GAC filters removed on average 60 to 70 percent of long-chain PFAS and about 40 percent of short-chain PFAS.[37]

The effectiveness of removal technologies can depend on other factors. For example, the presence of other contaminants can complicate removal, and groundwater can be less difficult to treat than surface water because groundwater contains less organic matter (which can clog ion exchange and GAC filters). In addition, combining removal technologies can increase effectiveness, as can combining them with certain destruction technologies. According to agency documents, combining treatment technologies, known as a treatment train, can be used to improve the efficiency of overall treatment of PFAS. Treatment trains pairing destruction and removal technologies also ensure the PFAS-containing residue generated by the removal technology does not have be stored over the long term, but their overall efficiency of PFAS destruction is still an active area of research.

Figure 9: How reverse osmosis (RO) removes PFAS from source water



Source: GAO review of peer-reviewed journal and academic sources. | GAO-22-105088

[37]N.J. Herkert, J. Merrill, C. Peters, D. Bollinger, S. Zhang, K. Hoffman, P.L. Ferguson, D.R.U. Knappe, and H.M. Stapleton, "Assessing the Effectiveness of Point-of-Use Residential Drinking Water Filters for Perfluoroalkyl Substances (PFASs)," *Environmental Science and Technology Letters,* vol. 7, (Feb. 5, 2022) 178–184.

4.2 Current PFAS disposal technologies vary in effectiveness and are uncertain at full scale

Removal of PFAS from drinking water results in a concentrated, PFAS-contaminated residue in liquid or solid form. Other media contaminated with PFAS, such as soil or biosolids, can also be collected from contaminated sites. Technologies are available to dispose of these PFAS-containing materials in a landfill or underground injection well. However, as shown below in table 5, the effectiveness of these technologies is variable and uncertain, according to agency documents, interviews with experts, and scientific literature.

Table 5: Technologies to dispose of materials containing per- and polyfluoroalkyl substances (PFAS)

Technology	Effectiveness	Advantages	Limitations
Landfills	Effectiveness at full scale is uncertain.	Commercially available. Feasible, but depends on landfill. Exist across the country.	Many landfills lack effective engineering controls to prevent PFAS release, or monitoring to detect PFAS release when it occurs.
Underground injection wells	Effectiveness at full scale is uncertain.	Commercially available. Feasible, but requires monitoring.	Few wells accept PFAS. Wells can only store PFAS if it is contained in a liquid.

Source: GAO analysis of agency documents. | GAO-22-105088

Landfills. According to agency documents, one of the best options for disposal of PFAS is in landfills lined with clay, plastic or synthetic rubber polymers, or both. However, many older landfills lack such controls and overall effectiveness of landfills at full scale, across the U.S. and for long-term PFAS disposal, is uncertain.

This approach is recommended for solids containing PFAS, such as soil, firefighting foam, spent GAC filters, and ion exchange resins. However, agency officials told us that there are several challenges to disposal of PFAS in landfills. For example, state landfill controls may not be sufficient to contain PFAS, which can lead to PFAS contamination of local water sources as PFAS-containing liquids (i.e., leachate) leak out of the landfill. In addition, since there are no federal regulations specific to the management of PFAS in landfills, some states and municipalities are uncertain about their ability to manage PFAS safely over the long term, according to agency officials.[38]

As a result, it is often unclear how well PFAS are contained by landfills, and not all landfills are monitored to determine

[38]The Resource Conservation and Recovery Act establishes the framework for a national system of solid waste control. Subtitle D of the Act is dedicated to non-hazardous solid waste requirements, and Subtitle C focuses on hazardous solid waste. Regulations established under Subtitle D set minimum federal criteria for the operation of municipal waste and industrial waste landfills, including design criteria and location restrictions. States play a lead role in implementing these regulations. Regulations established under Subtitle C designate specific wastes as hazardous and set criteria for generators, transporters, and treatment storage and disposal of those hazardous wastes.

whether they are a source of PFAS contamination. For example, in a study of 101 closed landfills in Minnesota, the state found that the local groundwater at 98 of them contained PFAS.[39] At 59 of those landfills, the PFAS in groundwater exceeded state guidelines, and at 15 sites the levels were 10 times the state guidelines.

Landfills vary in how long they can effectively contain PFAS, depending on landfill type, site conditions, and the specific PFAS involved.[40] However, all landfills will eventually release PFAS unless they are maintained, monitored, and the leachate and gas are treated.[41] There are no federal requirements for PFAS monitoring in landfills and no finalized, published EPA method for detection of PFAS in leachate.

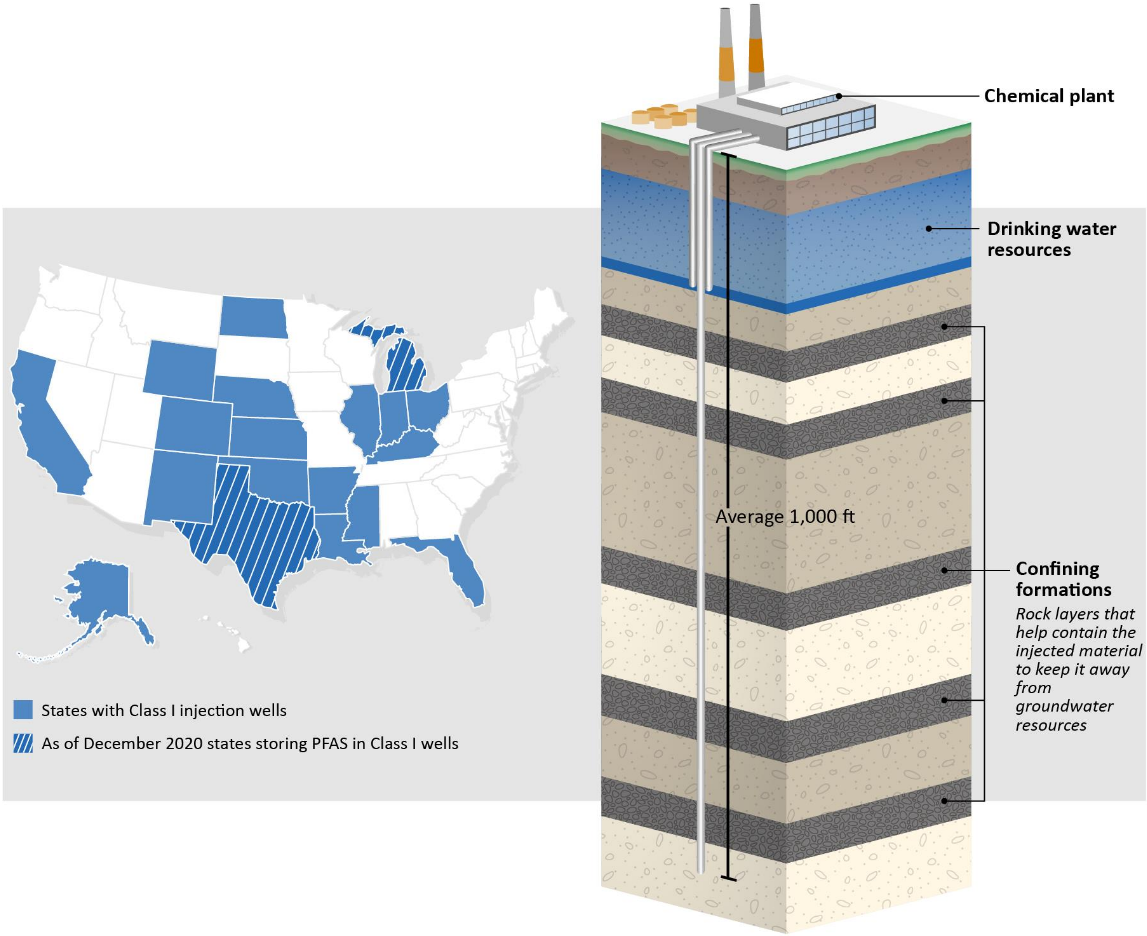
Underground injection wells. In addition to landfills, PFAS waste concentrated in liquid form may also be disposed of in an underground injection well. The ability of an injection well to effectively sequester hazardous waste depends on the waste being in liquid form and on the well's location and geology. In addition, the waste transportation costs affect the attractiveness of this approach to PFAS disposal. According to EPA, only Class 1 wells permitted for non-hazardous industrial and hazardous waste are currently being used for PFAS disposal. These wells are found only in deep, isolated rock formations, which can reduce the risk of release to public drinking water.

[39]PFAS in Landfills, Minnesota Pollution Control Agency, https://www.pca.state.mn.us/waste/pfas-landfills.

[40]Although municipal solid waste landfills in the U.S. since the early 1990s have been required to have controls (e.g., liners or leachate collection systems) that can minimize PFAS release via leachate or gas, approximately 6,000 landfills constructed prior to these requirements may be closed or not have such controls.

[41]Leachate captured via controls is typically treated with conventional activated sludge processes in a wastewater treatment plant. However, studies have found these processes may have no effect, or appear to increase measured PFAS content, likely due to the conversion of undetectable PFAS precursors to detectable PFAS.

Figure 10: Map of deep injection wells and their use for PFAS, with a diagram of a deep injection well



Source: GAO analysis of U.S. Environmental Protection Agency guidance. | GAO-22-105088

Note: Not to scale.

4.3 Current and emerging destruction technologies have the potential to destroy all PFAS

Incineration is widely available as a thermal destruction technology for PFAS, and multiple other destruction technologies are in development (see table 6). However, it is not yet clear whether these technologies fully destroy all PFAS—that is, whether they completely convert all PFAS into other, more benign chemical forms. Nor is it clear whether they can be applied at full scale across the U.S.

Table 6: Technologies used to destroy per- and polyfluoroalkyl substances (PFAS)

Technology	Effectiveness	Advantages	Limitations
Incineration	Effectiveness at full scale depends on optimization of operating parameters.	Commercially available. May fully destroy PFAS.	Complete destruction requires > 1,000 °C. Inadequate temperature may result in products of incomplete combustion. Method for monitoring PFAS during incineration is not clear.
Supercritical water oxidation (emerging)	Effectiveness demonstrated at pilot scale but not at full scale.	Destroys select PFAS by 99% in a variety of media and at a fast rate (<1 minute).	High energy requirements, maintenance issues, scalability unclear.
Pyrolysis (emerging)	Effectiveness demonstrated at pilot scale, but not full scale.	Uses less energy than incineration. Some by-products of process may be used as fuel. Commercially available.	Some by-products may release PFAS back into environment. The share of PFAS destroyed may vary from roughly 54% to 98%, depending on the specific PFAS.

Source: GAO analysis of agency and industry documents. | GAO-22-105088

Incineration is a type of thermal destruction that has generally been applied to water treatment residuals such as filters or resins following their contact with PFAS, but it has also been applied to PFAS-contaminated soil chemical manufacturing wastes, and unused firefighting foam.[42] During the incineration process, PFAS molecules may be broken into pieces, some of which may be shorter-chain PFAS.

The effectiveness of PFAS incineration at full scale depends on optimization of temperature, time, and the mixing of materials being combusted. For example, in limited laboratory-scale studies, PFOA (one type of PFAS) was reduced to undetectable levels after 2 seconds at 1,000° C.[43] Hazardous waste kilns and commercial hazardous waste incinerators using afterburners can exceed this temperature, but more common types of incinerators

[42]The activated carbon in spent GAC filters can be incinerated, disposed of in landfills, or regenerated in carbon reactivation furnaces that also destroy organic pollutants that are adsorbed to the spent carbon.

[43]Environmental Protection Agency, *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances* (Washington, D.C.: 2020).

may not. Specifically, 1000° C is at the upper end of operating conditions for municipal waste combustors and beyond the limit of sewage sludge incinerators. According to EPA's December 2020 Interim Guidance on Destruction and Disposal of PFAS, the U.S. had 193 municipal waste combustors and 170 sewage sludge incinerators, compared to 10 commercial hazardous waste incinerator facilities and 12 hazardous waste kilns.[44]

Another reason for uncertainty over the effectiveness of incineration, as well as other destruction methods, is that there is currently no finalized EPA method that can identify and quantify all the PFAS in air. This makes it impossible to determine the extent to which PFAS may be released into the air via the stack gas exiting the incinerator. Furthermore, if incineration of PFAS is not fully optimized, it can generate products of incomplete combustion—potentially harmful compounds that are currently undetectable by EPA methods. EPA has a draft test method, Other Test Method (OTM) 45, which measures 50 PFAS in air samples.[45] However, experts told us it cannot measure all airborne PFAS and is only a "good starting point" for monitoring PFAS levels after incineration.

According to experts and agency documents, more guidance, research, and data collection are needed to optimize the full process of PFAS incineration.[46] Experts told us they are uncertain how to measure PFAS going into an incinerator (the feed), what comes out (stack gases), and what is left inside the incinerator after the process is complete (residue). They also noted a lack of guidance for monitoring PFAS that may already be present in the air at a facility, which could reduce the accuracy of measuring the level of destruction.

Supercritical water oxidation uses intense chemical reactions, high temperatures (705 °C or hotter) and pressure (more than 200 times atmospheric pressure) to break the carbon-fluorine bonds in PFAS. This technology has achieved 99 percent destruction of targeted PFAS in pilot scale demonstrations.

Pyrolysis, another emerging technology, appeared to completely destroy PFAS in biosolids during prototype testing at lower temperatures (and requiring less energy)

[44]Environmental Protection Agency, *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances* (Washington, D.C.: 2020).

[45]According to EPA experts, there is currently no timetable for validating OTM-45.

[46]On December 18, 2020, EPA released for public comment new interim guidance to identify and describe technologies that may control releases of PFAS waste to protect human health and the environment. The interim guidance outlines the current state of the science on techniques and treatments that may be used to destroy or dispose of PFAS and PFAS-containing materials from non-consumer products, including aqueous film-forming foam (used for firefighting). The public comment period on this guidance closed on February 22, 2021 and EPA intends to publish revisions to the interim guidance by December 2023, as required by law. The interim guidance can be found at: https://www.epa.gov/pfas/interim-guidance-destroying-and-disposing-certain-pfas-and-pfas-containing-materials-are-not.

than those used for incineration.[47] This process also resulted in useful by-products, such as hydrogen-rich gas that can be used for fuel and a carbon-rich solid (biochar) that can be used for agriculture. The process is commercially available. However, it has yet to be confirmed whether the biochar will later release PFAS, and gaseous compounds generated during the process will need to be treated for other contaminants.

4.4 Challenges affecting PFAS treatment technologies

We identified the following four challenges to further developing and applying PFAS treatment technologies and methods.

Cost. The cost of full-scale PFAS treatment is highly uncertain, according to experts we spoke to and agency documents we reviewed. This uncertainty presents a challenge to planning and budgeting. Experts noted that better cost data could help water utilities determine where removal technologies could be applied to most efficiently protect human health. However, cost information may not exist at the needed scale because of limited research into the economics of PFAS removal from drinking water.

The estimates that are available suggest that cost will be high for some technologies. For example, according to the American Water Works Association, if GAC treatment were installed across the U.S. to meet the prior EPA Lifetime Drinking Water Health Advisory level for PFOA and PFOS (below 70 ppt), the cost could range from $2.1 to $4.4 billion.[48] This organization also developed a cost estimate of $23 to $50 billion to meet a lower requirement of 20 ppt—a level that some states have set as a treatment guideline. To put these figures in context, public spending on all water utilities in 2017, according to an agency document, was $113 billion.

For cities and towns, these costs could impact budgets and increase residents' water bills. For example, building a reverse osmosis facility that could meet PFAS treatment goals for a water system in Maine was estimated to cost between $57 and $85 million.[49] Repayment could double the municipality's budget and double or triple customers' water bills, according to the estimate.

Lack of methods and guidance. Representatives we interviewed from the

[47]Biosolids are a product of the wastewater treatment process. During wastewater treatment, the liquids are separated from the solids, which are further treated to produce a semisolid, nutrient-rich product known as biosolids. The terms "biosolids" and "sewage sludge" are often used interchangeably. Certain biosolids have been applied to farmland for nutrient addition, improved soil structure, and water reuse, but have also been found to contain PFAS.

[48]American Water Works Association, *Letter to Congressional Budget Office*, Aug. 8, 2019. Available online at https://www.awwa.org/Portals/0/AWWA/ETS/Resources/AWWAInformationforCBOforPFASTreatmentCosts.pdf?ver=2019-10-23-113359-787.

[49]CDM Smith, *Cost Analysis of the Impacts on Municipal Utilities and Biosolids Management to Address PFAS Contamination*, October, 2020. https://www.cdmsmith.com/en/Client-Solutions/Insights/PFAS-Biosolids

hazardous waste treatment industry noted there is a lack of best practices, validated methods, federal regulations, and guidance for treating PFAS. For example, incineration industry representatives said they are unsure how they should measure PFAS prior to incineration, what compounds they should measure while destruction is occurring, and what level of destruction is needed. Without this information, it is difficult to optimize incineration processes for full and effective destruction of PFAS.

A lack of federal guidance regarding PFAS disposal can make state and municipal landfill operators hesitant to accept PFAS waste, according to agency experts. DOD experts we spoke with also noted they continue to be challenged by the scarcity of validated and EPA-approved disposal options. In addition, the lack of multi-laboratory validated PFAS detection methods across most environmental media, but especially landfill leachate and landfill gas, contributes to uncertainty about the effectiveness of landfill storage of PFAS.

Chemical structure. Some PFAS compounds are more difficult to break down, which can limit the effectiveness of treatment and increase the cost of remediation. Other PFAS compounds are easier to break down but can form new compounds during incineration, making it difficult to determine the efficiency of destruction. PFAS in the environment may also degrade into different PFAS compounds, which may be harder to identify or treat. These changes can also make it hard to know whether treatment technologies are effective.

No full-scale, fully effective destruction technology. No PFAS destruction technologies have been effectively demonstrated to fully destroy PFAS at full scale. Current full-scale destruction technologies are not optimized for PFAS destruction, and most new PFAS destruction technologies are still at the research scale, according to agency documents. New PFAS destruction technologies are also limited by inefficiency, high energy consumption, and cost. For example, supercritical water oxidation may be able to destroy all PFAS, but it uses high amounts of energy and requires emission controls. Maintenance can also be difficult and costly because of the intense heat, pressure, and corrosive by-products generated during treatment. These factors can increase the cost of treatment using supercritical water oxidation and may limit the scale at which it can be deployed.

5 Policy Options

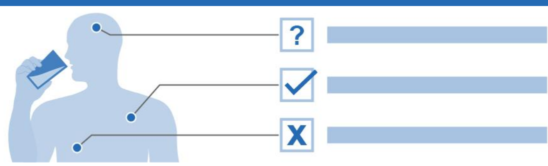
GAO identified three policy options that could help mitigate the challenges associated with PFAS assessment, detection, and treatment technologies. Policymakers could also choose to maintain the status quo—that is, allow current efforts to proceed without intervention. The relevant policymakers could include Congress, federal agencies, state and local governments, academic research institutions, and industry. While some challenges described in this report may be addressed through current efforts, other challenges may not be resolved, may be exacerbated, or may take longer to resolve without intervention.

Promote research

Policymakers could support development of technologies and methods to more efficiently research PFAS health risks.

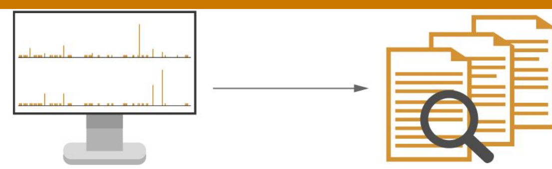
This policy option could help address the challenge of limited information on the large number and diversity of PFAS, as well as a lack of standardized data sets for machine learning.

Opportunities



- Promoting research for predictive methods could allow researchers to more efficiently assess PFAS as groups rather than individually. For example, according to experts, grouping PFAS could allow researchers to more efficiently prioritize certain PFAS for further testing, based on generalizable toxicity information for other PFAS in the same class.
- Integrating existing PFAS health information from multiple studies could result in better information sharing among researchers, which may lead to more efficient health assessments of the wide range of PFAS. Tools for integration include systematic evidence maps, which could help researchers identify emerging trends, data gaps, and evidence clusters in PFAS health assessments.
- Supporting technologies for more efficient research could also improve the assessment of alternatives to PFAS. For example, machine learning could improve efforts to find non-PFAS alternatives that have the same desired properties as PFAS, such as heat-resistance, but without the same adverse health effects.

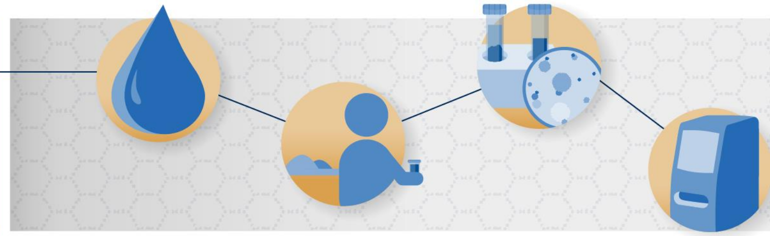
Considerations



- Computer models for more efficiently researching PFAS may not be sufficient on their own to accurately assess health effects. In particular, current technology may not reliably predict complex health outcomes because of a lack of scientific knowledge on the behavior of PFAS in the human body.
- Machine learning is early in development for PFAS health assessments, and researchers lack complete or standardized data sets to train and validate machine learning models. Developing these data sets may require extensive time and resources before such models can be used for PFAS assessment.

Source: GAO. | GAO-22-105088

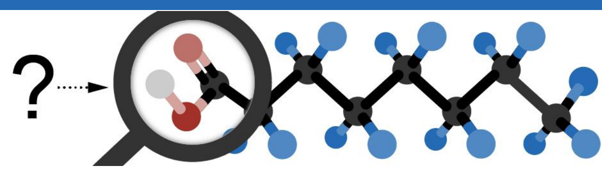
Expand method development



Policymakers could collaborate to improve access to reliable samples of PFAS, known as analytical standards, and increase the pace of method and reference sample development for PFAS detection.

This policy option could help address the challenges of a lack of validated methods in media other than water, lack of analytical standards, and cost. All of these challenges affect researchers' ability to develop new detection technologies.

Opportunities



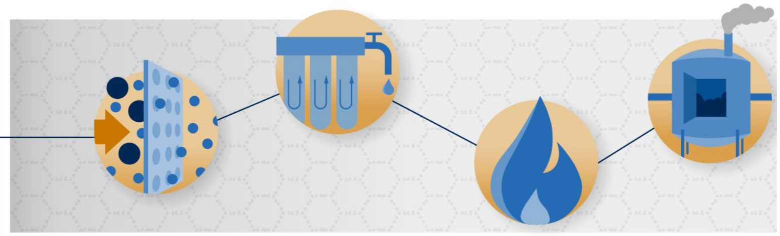
- Could increase access to standard reference samples of individual PFAS, known as analytical standards. Analytical standards allow researchers to identify and quantify specific PFAS in a sample, which is a vital aspect in the development of new PFAS methods. One way to improve access to these standards would be to support efforts by federal and independent laboratories to develop reference samples for known PFAS that would be available and affordable for researchers.
- Could enable researchers to accelerate development of new detection methods for media other than water. For example, finalization of methods for detection of PFAS in air, soil, or leachate could enable researchers to discover and reliably characterize more PFAS.
- Could enable development and finalization of a standard method for high resolution mass spectrometry. Experts noted that such a method would enable better screening and identification of PFAS in the environment. Such improvements to detection would help researchers and officials target sites where contamination is most likely to affect human health.

Considerations

- Private industry has been reluctant to provide analytical standards, many of which are considered proprietary. This has hindered researchers' efforts to study PFAS contamination in the environment and develop detection methods. To address this concern, experts suggested that policymakers could collaborate on agreements that encourage manufacturers to provide samples of PFAS for research and method development while preventing disclosure of proprietary information.
- Some end users may struggle to apply additional methods for PFAS detection even after they are developed, leaving the populations they serve still at risk. For example, one expert we interviewed noted that contract laboratory analysis could cost up to $500 per sample. These costs may be prohibitive for private well owners and smaller water utilities. Additional funding or other resources may be needed to protect populations who rely on these sources for drinking water.

Source: GAO. | GAO-22-105088

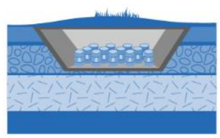
Support full-scale treatment



Policymakers could encourage the development and evaluation of full-scale technologies and methods to dispose of or destroy PFAS.

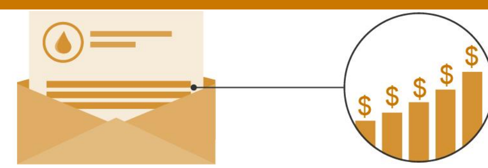
This policy option could help address the challenges of cost and efficiency of disposal and destruction technologies and a lack of guidance from regulators.

Opportunities



- Could support optimization of full-scale disposal and destruction technologies for PFAS by encouraging finalization of EPA methods. For example, policymakers could encourage finalization of EPA method OTM 45, which is designed to measure 50 PFAS in air and which experts told us is a “good starting point” for monitoring PFAS levels after incineration.
- Could collaborate to promote better integration of different technologies (creating what are known as treatment trains) to more efficiently dispose of and destroy PFAS in a variety of environments and settings across the U.S. State and local officials could also share information with each other about ongoing and past evaluations of the effectiveness and costs associated with the adoption and implementation of disposal and destruction options.
- Could encourage the development of guidance for monitoring PFAS release at landfills. Landfills vary by type and site conditions in how long they can effectively contain PFAS-contaminated materials from release into the environment via leachate or gas. PFAS-containing landfills require monitoring and testing to confirm PFAS do not contaminate underground sources of drinking water.
- Could accelerate the development and sharing of performance and cost models for disposal and destruction of PFAS in drinking water. Stakeholders, especially operators of smaller drinking water systems, may lack such information in general. This information could promote PFAS treatment and help water utilities and agencies better plan for future costs.

Considerations



- Technologies for destroying PFAS could be difficult to implement at scale, due to the lack of guidance from regulators. For example, officials from multiple agencies noted that more guidance is needed from regulators for the full process of incineration, which is currently the only option for long-term PFAS destruction at scale. This guidance should describe, among other things, how to measure the amount of PFAS entering, exiting, and remaining in the incineration chamber. Additional guidance is also needed on monitoring the amount of PFAS that may normally be present in an incineration facility. Such background levels may interfere with accurately measuring any airborne release of PFAS from incineration.
- In the absence of effective controls, landfills may release PFAS into the environment over time. Currently, there are no federal requirements for PFAS monitoring in landfills, leaving the full-scale effectiveness of this disposal method uncertain.
- Guidelines may drive up the cost of PFAS disposal and destruction, and currently vary by a considerable amount across the U.S. High costs associated with some options may significantly impact some municipalities’ budgets and raise residents’ water bills considerably.

Source: GAO. | GAO-22-105088

6 Agency and Expert Comments

We provided a draft of this report to the Department of Defense, the Department of Energy, the Department of Health and Human Services, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Institute of Standards and Technology, the National Science Foundation, and the Department of Agriculture with a request for technical comments. We incorporated agency comments into this report as appropriate.

We are sending copies of this report to the appropriate congressional committees, relevant federal agencies, and other interested parties. This report will be available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact Karen L. Howard at (202) 512-6888 or howardk@gao.gov or J. Alfedo Gómez at (202) 512-3841 or gomezj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix III.

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United States Senate

The Honorable Gary C. Peters
Chairman
The Honorable Rob Portman
Ranking Member
Committee on Homeland Security and Governmental Affairs
United States Senate

The Honorable Ron Johnson
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Permanent Subcommittee on Investigations
Committee on Homeland Security and Governmental Affairs
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The Honorable Mikie Sherrill
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Committee on Science, Space, and Technology
House of Representatives

The Honorable Haley Stevens
Chairwoman
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The Honorable Lizzie Fletcher
House of Representatives

Appendix I: Objectives, Scope, and Methodology

We examined (1) technologies, such as AI and machine learning, that might contribute to more efficient assessments of the safety and adverse health effects of per- and polyfluoroalkyl substances (PFAS) and alternative substances, (2) the benefits and challenges of current and emerging technologies for PFAS detection and treatment, and what gaps, if any, remain, and (3) policy options that are available to help enhance benefits and mitigate challenges associated with PFAS detection, treatment, and assessment technologies.

To address all three research objectives, we reviewed key reports and peer-reviewed articles; conducted a nongeneralizable survey with PFAS subject matter experts at federal agencies; and interviewed a variety of stakeholders, including agency officials, non-government organizations, industry, and researchers at academic institutions.

Scope

We focused our research on technologies that could improve the efficiency of PFAS health assessments and technologies for detection and treatment of PFAS in the environment, as well as the challenges with developing and using these technologies. We reviewed technologies addressing the efficiency of PFAS assessments including machine learning and artificial intelligence. We reviewed technologies addressing PFAS detection and treatment in the environment including targeted and non-targeted detection methods, as well as filtration and incineration technologies for treatment. We did not assess all possible technologies for PFAS assessment, detection, and treatment. For example, we excluded technologies used for detection and treatment of PFAS in consumer products, food, and biological samples. We also excluded discussion of assessments of the safety and adverse health effects of PFAS alternatives.

Interviews

We interviewed key stakeholders in the field of PFAS health assessments, detection, and treatment technologies, including:

- Eight relevant federal agencies that have offices or divisions that currently fund or conduct research on PFAS technologies for assessments of safety and adverse health effects, as well as detection and treatment in different environmental media: the Department of Defense, the Department of Energy, the Department of Health and Human Services, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Institute of Standards and Technology, the National Science Foundation, and the Department of Agriculture.
- Five non-government organizations with subject matter expertise related to PFAS assessments, detection, treatment, and policy.
- Three industry organizations that manufacture or use PFAS in their work, or represent the wide viewpoint of industry on the issues of PFAS environmental contamination including detection and treatment.

- Six academic institutions that had centers focused on PFAS research, testing, and environmental remediation.

Because we selected a small and nongeneralizable sample of stakeholders involved in funding, researching, and using PFAS health assessment, detection, and treatment, technologies, the results of our interviews are illustrative and represent important perspectives, but are not generalizable.

Literature search

For all objectives, we conducted scientific and policy literature searches for articles regarding PFAS assessment, detection, and treatment technologies, including their benefits and challenges. To gain insight into PFAS technologies' applications, potential benefits, challenges, and drawbacks, we reviewed agency documents, peer-reviewed literature, white papers, conference papers, industry articles, and other publications. A research librarian conducted scientific searches with Scopus using search terms related to these topics, including "per- and polyfluoroalkyl substances," "PFAS," "technology," "risk assessment," "toxicity," "health risks," "detection limits," "machine learning," "artificial intelligence," "disposal technologies," and "waste treatment" among a wide selection of keywords relevant to PFAS assessment, detection, and treatment technologies. For the scientific literature review, we considered articles that were published within the last 5 years.

For the policy literature search, a research librarian identified PFAS policies that have been enacted or proposed in the last 5 years using search terms including "PFAS regulations," "PFAS laws," "NDAA 2022," "Build Back Better Act," "PFAS detection," and "PFAS treatment". We conducted a content analysis of legislative literature using a categorization process for existing or prior policies on related issues, as well as potential new policy proposals to better understand what has already been done or attempted to address identified issues.

Survey

To address all of our objectives, we conducted a nongeneralizable survey of agency divisions with expertise on PFAS technologies for assessments, detection, and treatment. Our web survey consisted of 20 questions about the agency involvement and views on technologies for PFAS detection, removal, and destruction; assessing PFAS safety or adverse health effects; and identifying and assessing alternatives to PFAS. For example, we asked agencies about their involvement with researching or funding research into these technologies, the sufficiency of existing technologies, and the challenges associated with these technologies, among other things. We chose 35 divisions from the eight federal agencies in our review. To develop the questionnaire for the web survey, we reviewed agency documents and conducted a background literature search. In consultation with GAO's Applied Research and Methods (ARM) team, we conducted pre-testing of the questionnaire with two federal agencies to ensure clarity of the questions, ease of use, and completeness of our questions.

We asked federal agency officials to select and provide contact information for PFAS subject matter experts within divisions that represented at least one of the following areas: 1) technologies used to assess the safety, adverse health effects, and alternatives to PFAS and 2) technologies currently used for analyzing, quantifying, and treating PFAS in the environment including water, air, and soil. We also requested that only one response be submitted per division within an agency, but encouraged experts within that division to collaborate and provide a combined response. Because the expertise required for the survey was so specific, only certain divisions or agencies within a department were identified as potential respondents: for example, within the Department of Health and Human Services, we worked with the National Institutes of Health (including the National Cancer Institute and the National Institute of Environmental Health Sciences), and the Centers for Disease Control and Prevention, among others. Because we selected a small, targeted sample of federal agencies, our survey results are illustrative and represent important perspectives from a specific set of experts on certain PFAS technologies, but are not generalizable to all experts or all PFAS technologies. Across these agencies, we sent the survey to 35 divisions and received 30 survey responses (an 86 percent response rate) from seven of the eight agencies. Throughout the report, results of the survey are presented as a collection of information across all respondents, and are not specific to any one agency or division, unless otherwise noted.

Policy options

We intend policy options to provide policymakers with a broader base of information for decision-making.[50] Policy options are not formal recommendations for federal agencies, or matters for congressional consideration, but they are intended to represent possible options policymakers can take to address a policy objective. They are also not listed in any specific rank or order. We are not suggesting that they be done individually or combined in any particular fashion. Additionally, we did not conduct work to assess how effective the options may be, and express no view regarding the extent to which legal changes would be needed to implement them.

We developed three policy options to enhance the benefits and mitigate the challenges of PFAS technologies. To develop the policy options, we identified 114 policy ideas based on a literature review, a survey, and interviews with federal agencies, non-government organizations, industry groups, and academic researchers. We generated policy options by grouping policy ideas by themes that addressed objectives 1 and 2 and fit the scope of our work. We assessed each policy option by identifying potential opportunities and considerations of implementing them, as identified over the course of the review.

We conducted our work from March 2021 to July 2022 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The

[50]The term "policymakers" is a broad term including, for example, Congress, federal agencies, state and local governments, academic and research institutions, and industry.

framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

Appendix II: Selected Federal Statutes and Related Agency Actions Concerning Per- and Polyfluoroalkyl Substances (PFAS)

Federal statutes	Select provisions and related actions
The National Defense Authorization Act (NDAA) for Fiscal Year 2020	The NDAA for Fiscal Year 2020, enacted in December 2019, included language that, among other things: • Prescribed guidelines for the Department of Defense (DOD) disposal of certain materials containing PFAS; • Included provisions to facilitate DOD sharing of PFAS monitoring data with states and municipalities; • Set priorities for the Environmental Protection Agency's (EPA) research on PFAS and monitoring of drinking water; • Calls on DOD to ensure that a PFAS-free firefighting agent is available for use by October 1, 2023, because DOD will be prohibited from using PFAS-containing foams at installations starting on October 1, 2024; • Required EPA to publish interim guidance on the destruction and disposal of PFAS; • Required EPA to develop tools to characterize and identify PFAS in drinking water, wastewater, surface water, groundwater, solids, and the air; and • Added certain PFAS to the Toxics Release Inventory.
NDAA for Fiscal Year 2022	The NDAA for Fiscal Year 2022, enacted in December 2021, included language that, among other things: • Required DOD to establish a task force to address the effects of the release of PFAS from DOD activities; • Put a temporary moratorium on incineration by DOD of certain materials containing PFAS; • Required public disclosure of results of DOD testing of water in certain areas for PFAS; and • Extended DOD's authority to pay for a study and assessment of health implications of PFAS contamination in drinking water through 2023.
Clean Water Act	The Clean Water Act aims to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." EPA identified PFAS as a topic for future investigation in a 2016 plan related to implementing the act. The plan stated that EPA will examine surface water discharges from industrial categories using PFAS. However, relatively few facilities have permit limits or monitoring requirements for PFAS, in part because EPA has not developed national effluent limitations for PFAS under the act.
Safe Drinking Water Act (SDWA)	The SDWA requires EPA to establish requirements for public water systems to monitor for certain unregulated contaminants. EPA's Third Unregulated Contaminant Monitoring Rule (UCMR3) required monitoring of six PFAS between 2013 and 2015. EPA's fifth rule, UCMR5, calls for monitoring of 29 PFAS from public water systems between 2023 and 2025.
Toxic Substances Control Act of 1976 (TSCA)	TSCA, as amended, authorizes EPA to review chemicals already in commerce and chemicals yet to enter commerce, obtain more information on the effects of chemicals on human health and the environment, and regulate those that EPA determines pose unreasonable risks to human health or the environment. EPA has used TSCA to require companies to provide notice to EPA of significant new uses of certain PFAS in products before those products are manufactured, imported, or sold in the U.S.

Federal statutes	Select provisions and related actions
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)	CERCLA authorizes the federal government to respond to releases or threatened releases of hazardous substances and created a trust fund to provide for certain cleanup activities. No PFAS are currently designated as hazardous substances under CERCLA, though EPA considers them to be pollutants or contaminants. However, in January 2021, we reported that the National Aeronautics and Space Administration (NASA) was in the process of conducting preliminary assessments, under the authority of CERCLA, at 15 locations where past or present NASA activities may have resulted in a release of PFAS into the environment.[a] According to NASA officials, the preliminary assessments revealed areas of concern at several locations.

Source: GAO review of published federal statutes. | GAO-22-105088

[a]GAO, *Environmental Liabilities: NASA's Reported Financial Liabilities Have Grown, and Several Factors Contribute to Future Uncertainties*, GAO-21-205 (Washington, D.C.: January 15, 2021).

Appendix III: List of PFAS Covered by the Environmental Protection Agency's Detection Methods for Water

PFAS	Drinking water methods	Drinking water methods	Non-drinking water method
PFAS descriptor	*533*	*537.1*	*8327*
11Cl-PF3OUdS	covered by method	covered by method	not covered by method
9Cl-PF3ONS	covered by method	covered by method	not covered by method
ADONA	covered by method	covered by method	not covered by method
HFPO-DA[51]	covered by method	covered by method	not covered by method
NFDHA	covered by method	not covered by method	not covered by method
PFBA	covered by method	not covered by method	covered by method
PFBS	covered by method	covered by method	covered by method
8:2FTS	covered by method	not covered by method	covered by method
PFDA	covered by method	covered by method	covered by method
PFDoA	covered by method	covered by method	covered by method
PFEESA	covered by method	not covered by method	not covered by method
PFHpS	covered by method	not covered by method	covered by method
PFHpA	covered by method	covered by method	covered by method
4:2FTS	covered by method	not covered by method	covered by method
PFHxS	covered by method	covered by method	covered by method
PFHxA	covered by method	covered by method	covered by method
PFMPA	covered by method	not covered by method	not covered by method

[51]Hexafluoropropylene oxide (HFPO) dimer acid and its ammonium salt are also referred to as GenX chemicals.

PFAS	Drinking water methods	Drinking water methods	Non-drinking water method
PFAS descriptor	*533*	*537.1*	*8327*
PFMBA	covered by method	not covered by method	not covered by method
PFNA	covered by method	covered by method	covered by method
6:2FTS	covered by method	not covered by method	covered by method
PFOS	covered by method	covered by method	covered by method
PFOA	covered by method	covered by method	covered by method
PFPeA	covered by method	not covered by method	covered by method
PFPeS	covered by method	not covered by method	covered by method
PFUnA	covered by method	covered by method	covered by method
PFTrDA	not covered by method	covered by method	covered by method
PFTA	not covered by method	covered by method	covered by method
NEtFOSAA	not covered by method	covered by method	covered by method
NMeFOSAA	not covered by method	covered by method	covered by method
PFNS	not covered by method	not covered by method	covered by method
PFDS	not covered by method	not covered by method	covered by method
PFSOA	not covered by method	not covered by method	covered by method
Total PFAS covered	**25**	**18**	**24**

Legend: A ✓ means PFAS compound is covered by method; A - means PFAS compound is not covered by method.

Source: GAO analysis of agency documents. | GAO-22-105088

Appendix V: GAO Contacts and Staff Acknowledgments

GAO contacts

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