Characterizing PFAS Chemistries, Sources, Uses, and Regulatory Trends in U.S. and International Markets

Final White Paper

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Acronyms and Abbreviations

ADME	Absorption, Metabolism, Distribution, and Excretion
AFFF	Aqueous Film-Forming Foam
ALT	Alanine Aminotransferase
APFO	Ammonium Pentadecafluorooctanoate
ATSDR	Agency for Toxic Substances and Disease Registry
BEA	Bureau of Economic Analysis
BPA	Bisphenol A
BPS	Bisphenol S
CAGR	Combined Annual Growth Rate
CASRN	Chemical Abstracts Registry Number
CBI	Confidential Business Information
CDC	Centers for Disease Control and Prevention
CDR	Chemical Data Reporting
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
C-F	Carbon–Fluorine
CLG	Chemistry Laboratory Guidebook
Cl-PFESA	Chlorinated Polyfluorinated Ether Sulfonate
COVID	Coronavirus Disease 2019
CPC	Cooperative Patent Classification
CPSC	Consumer Product Safety Commission
DTXSID	DSSTox Substance Identifier
DWR	Durable Water Repellent
ECHA	European Chemicals Agency
EFSA	European Food Safety Authority
EPA	Environmental Protection Agency
FASA	Perfluoroalkane Sulfonamides
FCM	Food Contact Materials
FDA	Food and Drug Administration
FEP	Fluorinated Ethylene Propylene
FGR	Fetal Growth Restriction
FTCA	Fluorotelomer Carboxylic Acid
FTOH	Fluorotelomer Alcohol
FTSA	Fluorotelomersulfonic Acid
GenX	Hexafluoropropylene Oxide Dimer Acid and Its Ammonium Salt
HBWC	Health-Based Water Concentration
HFPO-DA	Hexafluoropropylene Oxide Dimer Acid (GenX)
HI	Hazard Index
HPCDS	High Priority Chemicals Data System
HPDE	High Density Polyethylene
HS	Harmonized System
IARC	International Agency for Research on Cancer
IRIS	Integrated Risk Information System
ITRC	Interstate Technology Regulatory Council
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal

MRL	Minimal Risk Level
NAICS	North American Industry Classification System
NASEM	National Academies of Science, Engineering and Medicine
NTP	National Toxicology Program
OECD	Organisation for Economic Co-operation and Development
PBT	Persistent, Bioaccumulative, and Toxic
PFAA	Perfluoroalkyl Acid
PFAS	Perfluoroalkyl and Polyfluoroalkyl Substances
PFBA	Perfluorobutanoic Acid
PFBS	Perfluorobutanesulfonic Acid
PFCA	Perfluoroalkyl Carboxylic Acid
PFDA	Perfluorodecanoic Acid
PFDoA	Perfluorododecanoic Acid
PFDS	Perfluorodecane Sulfonic Acid
PFEA	Perfluoroalkyl Ether Acids
PFHpA	Perfluoroheptanoic Acid
PFHpS	Perfluoroheptane Sulfonic Acid
PFHxA	Perfluorohexanoic Acid
PFHxS	Perfluorohexanesulfonic Acid
PFNA	Perfluorononanoic Acid
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctanesulfonic Acid
PFOSA	Perfluorooctanesulfonamide
PFOSF	Perfluorooctanesulfonyl Fluoride
PFPE	Polymeric Perfluoropolyethers
PFPeA	Perfluoropentanoic Acid
PFSA	Perfluorosulfonic Acid
PFUdA	Prefluorododecanoic Acid
PFUnA	Perfluoroundecanoic Acid
PTFE	Polytetrafluoroethylene
RCR	Risk Characterization Ratio
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RD	Reference Dose
RSC	Relative Source Contribution
SDWA	Safe Drinking Water Act
SPF	Sun Protection Factor
SVHC	Substances of Very High Concern
SWIFT	Sciome Workbench for Interactive Computer-Facilitated Text-Mining
TFE	Tetrafluoroethylene
TOF	Total Organic Fluorine
TRI	Toxics Release Inventory
TSCA	Toxic Substances Control Act
TWI	Tolerable Weekly Intake
UCMR	Unregulated Contaminant Drinking Water Monitoring Rule
UOF	Unidentified Organofluorine
vPvB	Very Persistent and Very Bioaccumulative

Executive Summary

ES.1 Mission of CPSC and RTI

The Consumer Product Safety Commission (CPSC) is an independent federal agency that protects the public against unreasonable risk of injury or death from consumer products. CPSC “works to save lives and keep families safe by reducing the risk of injuries and deaths associated with consumer products” by:

- Issuing and enforcing mandatory standards;
- Obtaining the recall of products and arranging for a repair, replacement, or refund for recalled products;
- Researching potential product hazards;
- Developing voluntary industry standards;
- Informing and educating consumers; and
- Educating manufacturers worldwide (CPSC, n.d.).

RTI International is an independent, nonprofit research institute dedicated to improving the human condition by turning knowledge into practice. RTI is supporting the CPSC in developing a comprehensive white paper providing an overview of perfluoroalkyl and polyfluoroalkyl substance (PFAS) chemistries, sources, uses, and regulatory trends in U.S. and international markets, and a summary of completed exposure, hazard (toxicity), and risk assessments by authoritative bodies.

ES.2 Objectives of the White Paper

To provide an overview of PFAS, particularly as PFAS relate to consumer products, the objectives of this white paper are to:

- **Index** current and potential uses of PFAS in general consumer products and children’s products;
- **Describe** the lifecycle of PFAS and PFAS-containing products from initial production from raw materials to waste management;
- **Assess** market trends related to the supply and demand of PFAS and PFAS-containing products both domestically and internationally;
- **Summarize** local, state, federal, and international regulations enacted or proposed on PFAS;
- **Identify** current and potential alternatives for PFAS in consumer products;
- **Document** key sources of existing PFAS exposure assessments and risk assessments; and
- **Overview** the current state of science related to human health effects associated with PFAS exposure, including both cancer and noncancer health outcomes.

The information presented in this white paper is not a risk assessment. However, this white paper advances understanding of PFAS used in consumer products and associated potential exposure and health effects.

ES.3 PFAS Uses in Consumer Products Summary

PFAS are a group of chemicals with various definitions across academia, industry, supply chain producers, regulators, and others. Due to differing definitions, we compiled available sources from the U.S. Environmental Protection Agency to form a list of 16,229 distinct PFAS currently identified. We identified 863 PFAS with reported detections or uses in consumer products for their functional uses of friction reduction, grease/oil repellence, nonstick properties, stain resistance, and waterproofing.

> Out of 16,229 PFAS currently identified, 863 have reported use or detection in consumer products—either intentionally for their functional use—or as a byproduct, contaminant, or impurity from the manufacturing process.

Common consumer products categories with PFAS include apparel; children's products; containers and packaging; furniture, furnishings, and décor; and household products, such as nonstick cookware and cleaning solutions. Regarding apparel, studies have indicated that those labeled as stain-repellent or water-resistant (e.g., rain jackets) are often treated with PFAS. Similarly, children's products, such as bibs and clothing, have reported PFAS. Containers and packaging include disposable food packaging and food service ware (e.g., beverage cups and takeout containers); furniture, furnishings, and décor include carpets/rugs and other textiles. Recently, PFAS have also been detected in toilet paper along with other pulp and paper products. PFAS are also present in consumer products such as makeup foundation and sunscreen. Notably, consumer products may also contain PFAS unintentionally as a byproduct, contaminant, or impurity, from the manufacturing process. One potential source of the contamination in the manufacturing process is the use of PFAS as processing aids; however, there are still knowledge gaps in understanding unintentional PFAS in consumer products.

Ultimately, there is potential for human exposure during the use of PFAS-containing products within indoor environments. There is also potential for human exposure throughout the lifecycle of PFAS-containing consumer products as they are manufactured, processed, or disposed of and PFAS are released into the environment, including in ambient air; biosolids, compost, and other soil amendments used for agricultural operations; and groundwater and surface water. PFAS are mobile, therefore, release into one indoor or outdoor medium can result in occurrence in other environmental media through fate and transport processes.

ES.4 Market Trends Summary

PFAS production activity is concentrated in the chemicals sectors (defined as North American Industry Classification System [NAICS] 325 for reporting). The United States manufactures or imports over 2.5 billion pounds of PFAS per year on average. PFAS production and industrial releases are predominantly located in the eastern United States, from the Texas Gulf Coast north and east to Massachusetts. Manufacturers of other chemicals in and products within NAICS 325 (e.g., basic chemicals, resins and synthetic rubbers, pesticides and fertilizers, paint coatings and adhesives) comprise most domestic demand for PFAS. Internationally, polymers are the category of PFAS most actively traded by the United States. As a class, PFAS production trends in the United States appear largely steady over the past decade despite broader economic growth. Given these historical trends, continued economic growth may not bring additional PFAS production, though steady production would bring continued sources of PFAS into products and potential accumulation in the environment.

ES.5 Regulatory Trends and Alternatives

Federal and international regulations as of May 2023 have targeted a few individual PFAS (i.e., six PFAS—perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), perfluorohexanesulfonic acid (PFHxS), perfluorononanoic acid (PFNA), perfluoroheptanoic acid (PFHpA), and hexafluoropropylene oxide dimer acids and its ammonium salts [GenX chemicals]), whereas state regulations largely refer to bans on the entire class. States have several adopted and current policies aiming to prohibit the production or use of PFAS across consumer products categories with food packaging being among the most common prohibitions. As of May 2023, 13 states have adopted policies on PFAS-containing products and an additional 13 states have introduced policies.

PFAS are known to provide high performance at very low concentrations at highly economical costs, which has driven adoption and proliferation across several industries. However, with pending regulations, some industries are shifting to remove the class of PFAS rather than substituting for different PFAS. Some industries face larger barriers to substitution than others. In some applications, PFAS can be readily substituted with minimal impact on actual or perceived performance, while in other applications, PFAS are not as easily replaced due to high performance standards expected by end-users.

The primary chemistries emerging as potential substitutes for PFAS include silicones and siloxanes, anionic surfactants, nonionic surfactants, branched polymers, and hydrocarbon-based (non-fluorinated) solutions.

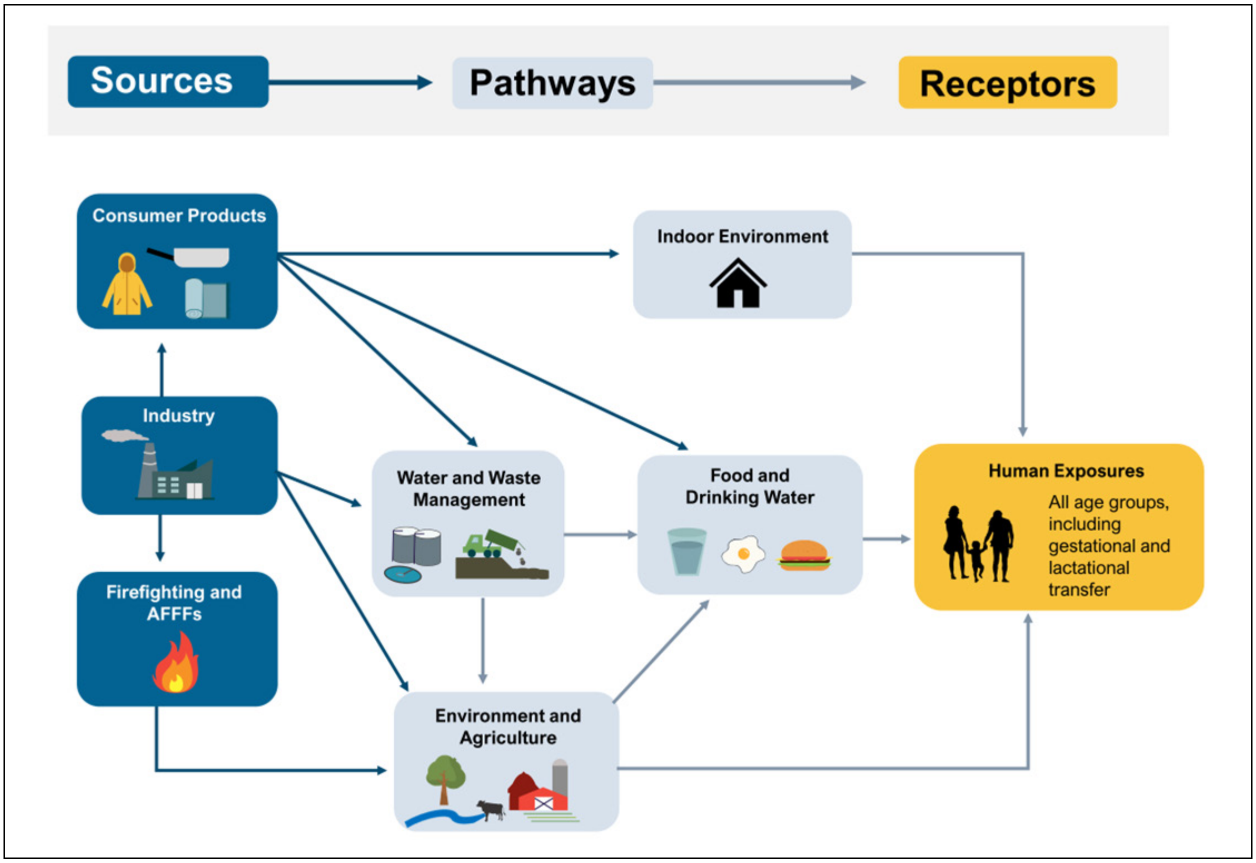
ES.6 Exposure and Human Health Summary

Most PFAS are persistent, and many are bioaccumulative—they can accumulate and magnify through the environment and food chains, resulting in many potential routes for human exposure and prolonged time frames for exposure. Ingestion of contaminated drinking water and food are the main human exposure pathways, and PFAS can remain in the human body long after exposures stop. Therefore, PFAS can build up in the body over time if exposures continue. Overall, additional research is needed on other exposure pathways, such as contact (i.e., dermal transfer and mouthing) and mediated exposure pathways related to consumer products use (i.e., inhalation of indoor air), to better inform the relative source contribution (RSC) among many different exposure pathways.

The different pathways in which humans are exposed directly or indirectly to PFAS are summarized in **Figure ES-1**.

PFOA and PFOS are the most thoroughly studied PFAS in the health and toxicity literature. Exposures to PFOA or PFOS are associated with a range of adverse health effects in the liver, immune system, early-life development, and cardiometabolic system. There is also growing evidence that exposures to PFOA, PFOS, and other similar PFAS are associated with endocrine disruption and reproductive effects. Notably, the International Agency for Research on Cancer (IARC) has classified PFOA as “possibly carcinogenic to humans (World Health Organization, 2016).” However, the diversity and number of PFAS make it more challenging to characterize health effects given the potential for cumulative exposures and health effects.

Figure ES-1. Overview of Select Exposure Pathways to PFAS



Source: Adapted from (Sunderland et al., 2019).

ES.7 Data Gaps, Limitations, and Uncertainties

This white paper provides a review of several topics related to PFAS in consumer products. The full protocol for this white paper can be found in **Appendix A**. This white paper should not be perceived as a comprehensive account of the state of the science of PFAS. Instead, data and reports published by authoritative entities were prioritized with peer-reviewed literature and other accounts used as supplements. Furthermore, there are several challenges in PFAS research and development. Across stakeholders—academia, industry, regulators, and others—there is still a lack of consensus on definitions, including what is considered a perfluoroalkyl or polyfluoroalkyl substance. Without a consistent definition, there can be misperceptions between manufacturers and suppliers, in addition to consumers and regulators. Additionally, the peer-reviewed literature and other reports describe very sensitive analytical methods. However, manufacturers are less likely to have analytical equipment and methods to detect PFAS at low concentrations. This mismatch can be a significant challenge when manufacturers are faced with reducing PFAS that can also be byproducts, contaminants, or impurities in the manufacturing process.

ES.8 Conclusions and Next Steps

This white paper provides an overview of PFAS, particularly as PFAS relate to consumer products. PFAS are synthetic chemicals, ubiquitous in consumer products and the environment.

Legacy chemicals—PFOA and PFOS, which have eight or more carbons—have been studied extensively with exposures associated with adverse human health outcomes, including decreased response to vaccines, dyslipidemia, kidney cancer, low birth weight, and others. Other legacy PFAS and those used as replacements for legacy chemicals, including perfluorobutanesulfonic acid (PFBS), perfluorodecanoic acid (PFDA), PFHxS, PFNA, and GenX chemicals, are less well-characterized, but there is an increasing amount of information describing associations with cancer and noncancer health outcomes. The general population is primarily exposed via ingestion of PFAS-contaminated drinking water and food; however, PFAS-containing products such as nonstick cookware and stain- and water-resistant apparel, contribute to aggregate exposures and are the subject of several current and proposed regulations.

Throughout the lifecycle of PFAS-containing products, there are several points of migration or release of PFAS or precursors into the environment including through emissions from manufacturing facilities, industrial discharge, and migration into landfills for municipal solid waste. The use-phase of the lifecycle where PFAS-containing products are directly used in indoor environments for several years presents an opportunity for continual emission into the indoor environment. However, this is less well-characterized when compared to lifecycle emissions into the outdoor environment. As the domestic and international supply and demand continues for PFAS and PFAS-containing products, these persistent chemicals will continue to contaminate the indoor and outdoor environments where individuals live and work. Reduction, and ultimately elimination, of PFAS use in consumer products and other applications is needed to reduce human exposure and associated adverse health outcomes. However, consensus across definitions and interpretations across stakeholders is needed first to help with awareness, communication, and selection of proper substitutions.

1. Introduction

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are ubiquitous in consumer products, the environment, and the blood of most Americans (Agency for Toxic Substances and Disease Registry [ATSDR], 2020). These manufactured chemicals have been produced and used for decades across several applications and industries. The physical-chemical properties of PFAS are desirable for use in carpets and rugs, cookware, food packaging, outerwear, and other products. In each of those products, the primary functional uses of PFAS are grease- and water resistance, among other properties. PFAS use in products is beneficial to both producers and users because of their durability and high performance (e.g., ability to keep stains off fabric and moisture out of products). However, PFAS use in consumer products can have adverse effects on the environment and public health based on potential human exposure.

> Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are ubiquitous in consumer products, the environment, and the blood of most Americans.

PFAS may persist in the environment and the human body for several years. Throughout academic research and the media, there have been numerous reports on the detection of PFAS in drinking water, groundwater, and surface waters, in addition to ambient and indoor air, indoor dust, and soil. PFAS can enter the indoor and outdoor environment at several points throughout their lifecycle.

PFAS Production: The production, or synthesis, of PFAS and PFAS-containing products at manufacturing facilities can result in PFAS contamination of air, soil, and water through accidental spills and/or intentional discharges and releases. Emissions into one medium can result in subsequent contamination of other media (i.e., wet deposition from air to groundwater and soil).

PFAS Use in Consumer Products: As consumer products are used and washed, PFAS may be released into the indoor and outdoor environments. The general population can be exposed both directly and indirectly through use. For instance, PFAS may be released from a rain jacket and directly contact skin. As that rain jacket is continually used and worn, PFAS may be released into indoor and outdoor air for the rain jacket user and others to inhale. Additionally, as the rain jacket is washed, PFAS may be released into the laundry water, which makes its way to the local wastewater treatment plant and surface waters.

End-of-Life Management: At the end-of-life, products are disposed of at municipal landfills or solid waste facilities. Waste management of those products can be a large source of PFAS released into the environment. For instance, the breakdown of PFAS-containing products may concentrate in landfill leachate, which can enter groundwater and soil if improperly managed, or the compost of PFAS-containing products (i.e., compostable food packaging) may be used in agricultural operations to produce fruits and vegetables. The lifecycle of PFAS-containing products creates a circular waste management issue whereby the initial production and use of PFAS-containing products accumulate into the environment, especially because PFAS compounds do not easily degrade.

Ultimately, the general population can be exposed to PFAS at any stage of their lifecycle, from ingestion of contaminated drinking water and food and inhalation of indoor air and dust to contact exposures with consumer products. Exposure to some of the most well-characterized PFAS (such as PFOA and PFOS that were commonly used in stain-resistant carpets and water-repellent apparel) are associated with decreased response to vaccines, elevated serum cholesterol, kidney cancer, liver damage, low birth weight, pre-eclampsia/pregnancy-induced hypertension, testicular cancer, and thyroid disease. Given the potential ecosystem impacts and safety concerns associated with PFAS use, experts in academia and industry have stated that PFAS-containing products should not be labeled as “sustainable.”

Increased awareness of PFAS use in consumer products and their potential health effects is increasingly leading consumers to look for products that are “PFAS-free.” Certain products consumers are searching for without PFAS include clothing, cookware, dental floss, menstrual period underwear, and makeup. To meet demand for this, some companies now use “PFAS-free” as a selling point in their marketing for new products. Subsequently, several questions arise: what *are* PFAS? How do we know in what they are produced and used? What gaps are there in our understanding of PFAS production and use in consumer products? How are state and federal governments and other countries starting to regulate and restrict PFAS use? What are the alternatives to PFAS use in consumer products?

In the next section, we will overview what PFAS are and set the stage for answering the questions above for consumers and regulators alike to understand PFAS sources, uses, and regulatory trends in the United States and internationally.

2. Background

2.1 PFAS Overview

Per- and polyfluoroalkyl substances, or PFAS, are a group of manufactured chemicals that have been used in consumer products and industry since the 1940s. Currently, there are thousands of PFAS associated with a broad range of uses. They are non-naturally occurring, yet-to-be regulated, environmental contaminants that have been detected in multiple environmental and biological media including air, drinking water, food, landfill leachate, indoor dust, soil, breast milk, and human blood.

PFAS are known to accumulate in the human body and have been linked to various toxicities. Data suggest that certain PFAS are toxic at low levels and that people may be exposed to multiple chemicals through various exposure pathways, in varying amounts, or as components of mixtures depending on where they live or work. Consumer products containing PFAS are one potential source of exposure to these potentially harmful chemicals. Research over the last two decades has focused on understanding the adverse effects of PFAS on human health and the environment and devising strategies to eliminate or substantially reduce exposures to PFAS.

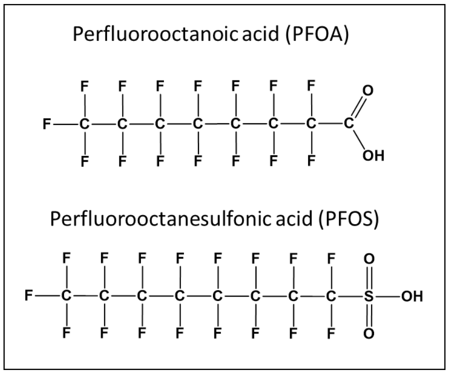
The study of PFAS is extremely challenging. New analytical methods have been and continue to be developed to identify and measure levels of these complex, ubiquitous chemicals in both environmental and biological samples and to assess the effectiveness of new treatment technologies for remediation. The following sections provide a description of the various structural classes of PFAS and an overview of analytical methods available for measuring PFAS in different media.

PFAS are commonly termed “forever chemicals” because they do not easily break down.

2.1.1 What Are PFAS?

The universe of chemicals that are considered PFAS is large and diverse. While PFAS can have different functional advantages and uses, they share common physical-chemical characteristics. As a class, PFAS generally have a carbon alkyl chain in which one or more hydrogen atoms attached to carbon atoms are substituted for fluorine atoms. The strong carbon-fluorine bonds in PFAS impart functional uses to the products that contain them, such as thermal stability and grease, stain, and water repellency, but these strong bonds also render PFAS environmentally persistent and resistant to complete degradation. PFAS are commonly termed “forever chemicals” because they do not easily break down. Additionally, some PFAS may simply be present in the environment as unintended byproducts of manufacturing or other processes. Examples of two well-known and widely studied perfluoroalkyl substances are depicted in **Figure 2-1**.

Figure 2-1. Chemical Structure of Perfluorooctanoic Acid and Perfluorooctanesulfonic Acid



2.1.2 PFAS Classes

The number of chemicals defined as PFAS is a subject of debate within the scientific community with varied opinions among academics, industry representatives, and regulators. Depending on the contextual definition of PFAS, the number generally ranges from hundreds to tens of thousands of chemicals, and lists are continually being updated by subject matter experts. For example, in 2018 the Organisation for Economic Co-operation and Development (OECD) released a report on a definition for PFAS that resulted in a list of 4,730 chemicals (OECD, 2018). Then, in 2021, OECD revised the definition for PFAS to include any substance containing at least one fully fluorinated carbon, increasing their estimate to more than 6 million compounds (Wang et al., 2021).

The U.S. Environmental Protection Agency (EPA) has curated PFAS lists from various sources and compiled these within their Computational Toxicology (CompTox) Chemicals Dashboard (U.S. EPA, n.d.-a). These lists represent different working definitions of PFAS and include fluorinated chemicals with and without explicit structures. The PFASSTRUCTV5 list, updated in August 2022, is currently the largest with 14,735 distinct PFAS.

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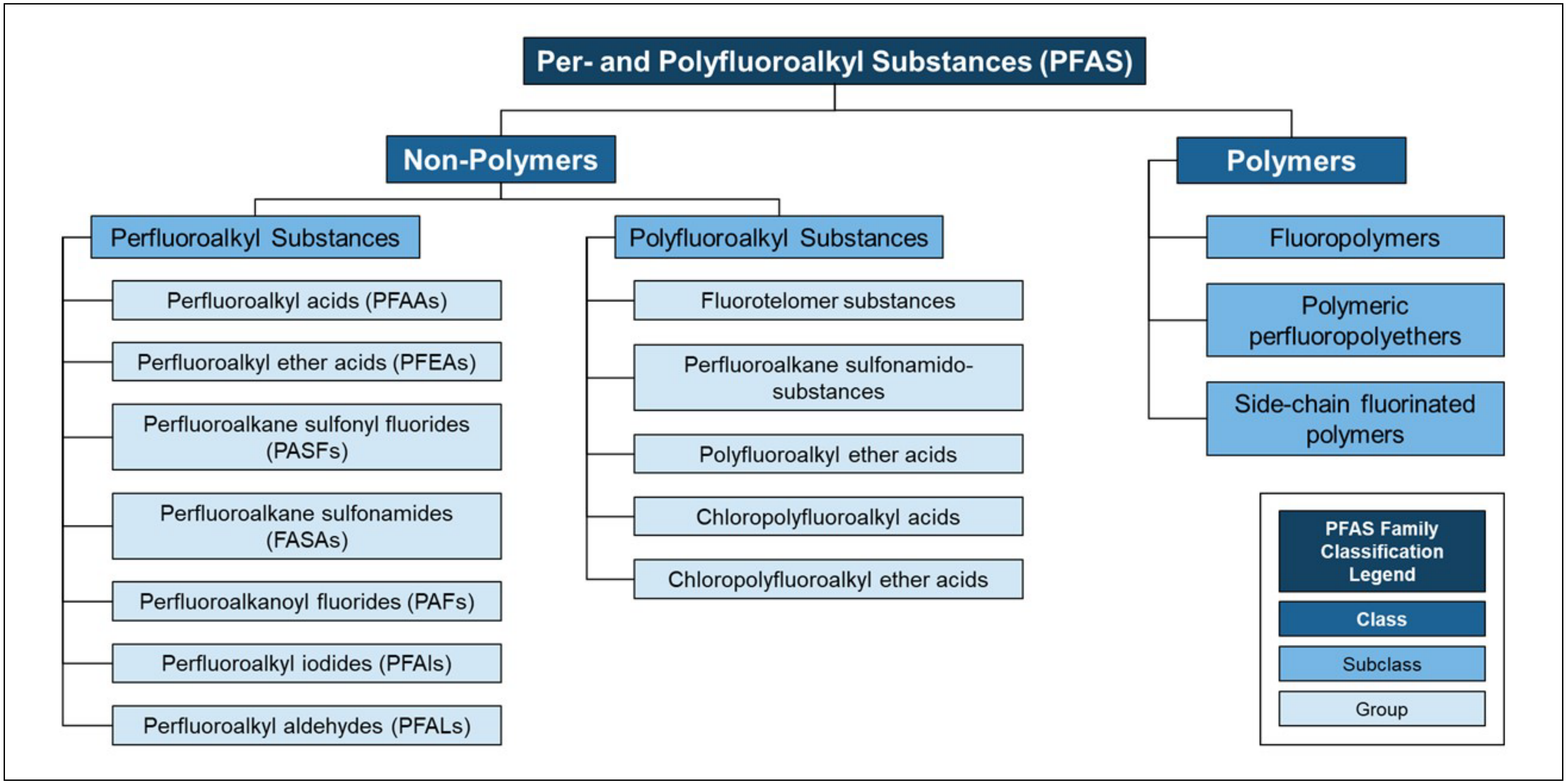
Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) both contain an 8-carbon alkyl chain, in which all the hydrogen atoms are replaced by fluorine atoms, and a polar head group (carboxylic acid and sulfonic acid for PFOA and PFOS, respectively). In addition to the linear structures depicted, these PFAS also exist as branched isomers with the same chemical formula and molecular weight but differ in the 3-dimensional arrangement of the atoms in their alkyl chains. PFOA and PFOS have been used for decades in the manufacture of consumer products and firefighting foams and have been key components in industrial processes such as electroplating and semiconductor production. They are referred to as terminal end-products because other PFAS (precursors) have the potential to transform into PFOA or PFOS upon oxidation, but PFOA and PFOS do not undergo further degradation themselves.

Given the compelling evidence for the association of PFOA and PFOS with adverse health outcomes, these two “C8 chemicals” were voluntarily phased out of production in the United States and have been termed “legacy” PFAS (U.S. EPA, n.d.-b). (“Legacy” PFAS compounds refer to PFAS with eight or more carbons.) In August 2022, the United States Environmental Protection Agency (U.S. EPA) proposed to designate PFOA and PFOS (including their salt forms and structural isomers) as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund (U.S. EPA, 2019). Manufacturers, however, continue to develop and produce novel per- and polyfluorinated chemicals as replacements with similar functional uses. These “emerging” PFAS, which contain shorter fluorinated alkyl chains and incorporate other functional groups (e.g., ether linkages), also need to be evaluated for potential risks to human health and the environment and associated exposure potential.

For this white paper, the universe of chemicals in the class of PFAS is divided into classes, subclasses, and groups based on structural similarities according to Buck et al. (2011). Collectively, these authors represent groups from fluorochemical manufacturers and other industries: environmental and public health departments, institutes, academic research groups; and consultants. The authors are one of the first to suggest nomenclature for families and groups of PFAS along with acronyms to aid communications among the scientific community, regulators, industry, and other groups (Buck et al., 2011). They defined two broad classes of PFAS, polymers and non-polymers, which are further divided into subclasses and groups based on chemical structures and functional groups (**Figure 2-2**).

Figure 2-2. PFAS Family Classification Scheme.



Source: Adapted from Buck et al. 2011 and the Interstate Technology & Regulatory Council, 2022.

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The three subclasses of polymers include fluoropolymers, polymeric perfluoropolyethers (PFPE), and side-chain fluorinated polymers. Non-polymer PFAS are divided into two subclasses: perfluoroalkyl substances, in which all carbon atoms in the alkyl chain are fully fluorinated, and polyfluoroalkyl substances, in which one or more, but not all, carbon-hydrogen bonds are replaced with carbon-fluorine bonds.

The groups belonging to the perfluoroalkyl subclass include perfluoroalkyl acids (PFAAs), perfluoroalkyl ether acids (PFEAs), perfluoroalkane sulfonyl fluorides, perfluoroalkane sulfonamides (FASAs), perfluoroalkanoyl fluorides, perfluoroalkyl iodides, and perfluoroalkyl aldehydes. Among the PFAAs group are carboxylic acids/carboxylates, sulfonic acids/sulfonates, and phosphorus-based acids. PFAAs include the legacy compounds—PFOA and PFOS—plus shorter-chain compounds like the 4-carbon chain perfluorobutanesulfonic acid (PFBS).

The polyfluoroalkyl substances subclass is represented by the following chemical groups: polyfluoroalkyl ether acids; fluorotelomer substances; perfluoroalkane sulfonamido substances; chloropolyfluoroalkyl acids; and chloropolyfluoroalkyl ether acids. Fluorotelomer substances are a large group consisting of alcohols, acids, iodides, olefins, alkenes, acrylates, aldehydes, and phosphates.

Additionally, throughout this white paper, we discuss ionic PFAS and neutral, volatile PFAS. Ionic PFAS include PFAAs and others, while neutral, volatile PFAS include fluorotelomer alcohols (FTOHs), acrylates, and methacrylates; perfluoroalkane sulfonamides; and others. Most importantly for this white paper, the distinction between ionic or neutral, volatile PFAS is significant for understanding of the fate and transport of PFAS throughout indoor and outdoor environments.

2.1.3 Well-Known PFAS

While many PFAS could be present in consumer and children's products, a limited number (dozens) of PFAS are included in environmental and biological monitoring and toxicological studies to date. PFAS were increasingly reported in environmental samples, particularly drinking and surface waters, in the early 2000s; however, PFAS have been produced and used since the 1930s. The early 2000s included several lawsuits and studies to determine whether the prevalent health effects among populations surrounding PFAS chemical plants and manufacturing facilities were linked to PFAS exposure.

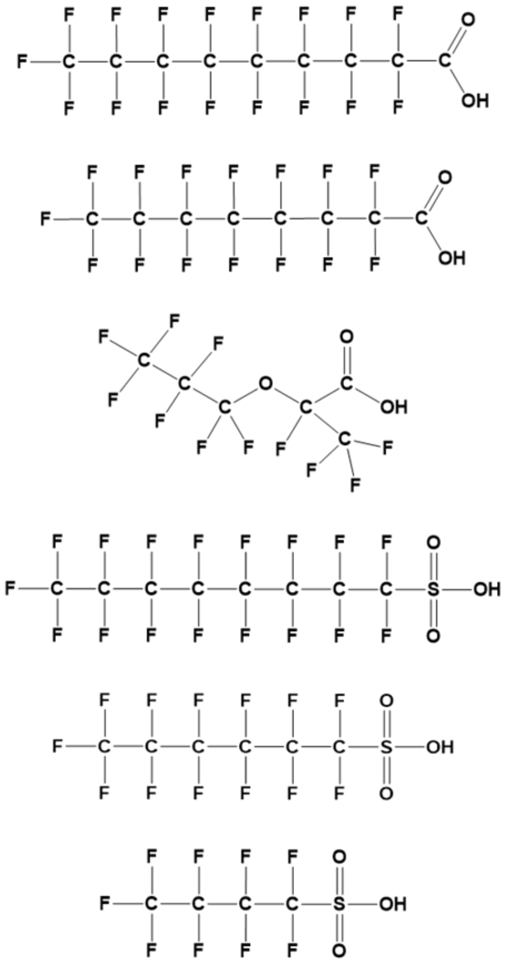
The most well-known PFAS to date include PFOA and PFOS, compounds used in nonstick cookware and stain-repellent products. A well-known replacement for PFOA is known as GenX.

One of those studies was the C8 Health Project, which examined mid-Ohio Valley residents living near a chemical plant that used PFOA for a brand name of polytetrafluoroethylene (PTFE). The residents were highly exposed to PFOA entering the groundwater and contaminating drinking water supplies largely due to releases from this chemical plant. The epidemiologists leading the C8 Health Project determined that high cholesterol, kidney cancer, pregnancy-induced hypertension, testicular cancer, thyroid disease, and ulcerative colitis have a probable link with PFOA. The C8 Health Project, and several other studies, have focused on exposure to PFOA and human health effects.

In addition to the legacy PFAS—PFOA and PFOS—more recently, a highly publicized emerging PFEA compound was identified in the Cape Fear River Basin in North Carolina due to direct emissions from a fluorochemical manufacturing facility (Sun et al., 2016). Hexafluoropropylene oxide dimer acid (HFPO-DA) is one of the chemicals in a manufacturing process known colloquially as GenX (Sun et al., 2016). HFPO-DA and other GenX chemicals were developed as replacements for PFOA, which had been used as a surfactant and as a processing aid in the production of fluoropolymers such as PTFE.

For well-known PFAS, chemical reference standards are available and analytical methods have been developed to assess their bioaccumulation, occurrence, and potential toxicological risks. Researchers are actively studying sources of human exposure to PFAS with PFAS-containing products (e.g., food packaging and textiles) and environmental exposures to PFAS leached from products sent to landfills. Many states have begun to set health advisories and exposure limits for certain PFAS as new data are generated, and in March 2023, the U.S. EPA announced their proposed National Primary Drinking Water Regulation for six well-known PFAS (U.S. EPA, 2023a; U.S. EPA, 2023b). The names and structures of these PFAS are presented in **Figure 2-3**.

Figure 2-3. PFAS Included in the Proposed U.S. EPA Primary Drinking Water Regulation



Perfluorononanoic acid (PFNA)
Molecular formula: C9HF17O2
Molecular weight: 464.08
CASRN: 375-95-1
DTXSID8031863

Perfluorooctanoic acid (PFOA)
Molecular formula: C8HF15O2
Molecular weight: 414.07
CASRN: 335-67-1
DTXSID8031865

Hexafluoropropylene oxide-dimer acid (HFPO-DA)
Molecular formula: C6HF11O3
Molecular weight: 330.05
CASRN: 13252-13-6
DTXSID70880215

Perfluorooctanesulfonic acid (PFOS)
Molecular formula: C8HF17O3S
Molecular weight: 500.13
CASRN: 1763-23-1
DTXSID3031864

Perfluorohexanesulfonic acid (PFHxS)
Molecular formula: C6HF13O3S
Molecular weight: 400.12
CASRN: 355-46-4
DTXSID7040150

Perfluorobutanesulfonic acid (PFBS)
Molecular formula: C4HF9O3S
Molecular weight: 300.10
CASRN: 375-73-5
DTXSID5030030

2.1.4 Methods for Testing PFAS

Analytical laboratory methods for detecting and measuring PFAS continue to be developed and validated for different media, including biomatrices, drinking water, soil, and wastewater. For instance, the Centers for Disease Control and Prevention (CDC) published a laboratory procedure for analysis in human serum, while the U.S. EPA has published standard methods for air emissions and drinking water (U.S. EPA, 2023c). The publication of those methods often sets the precedent for other entities, including state governments and researchers. However, those methods are limited in which PFAS can reliably be detected and measured.

For consumer and industrial products, ASTM International commonly sets standards. As of December 2022, ASTM International developed a new subcommittee to develop standards on PFAS present in consumer products. The standards are to cover a wide array of consumer products, and ultimately, help legislative and regulatory bodies and trade associations understand the presence of PFAS in consumer products (ASTM International, 2022).

While standards continue to be developed, current reports on PFAS in consumer products use different analytical methods, and therefore, may report concentrations based on specific PFAS, total fluorine (inorganic and organic), or total organic fluorine (TOF). As a result, this white paper also includes different indicators or measures of PFAS in consumer products and environmental media. Analytical methods can be categorized as *targeted* analyses or *non-targeted* analyses (NTAs).

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CDC Method 6304.09 is specific to the analysis of nine PFAS in human serum, while EPA Methods 533 and 537.1 are specific to the analysis of 25 and 18 PFAS, respectively, in drinking water (CDC, 2017; U.S. EPA, 2019; U.S. EPA, 2020). Another EPA method, Draft Method 1633 is currently undergoing multi-laboratory validation for the measurement of 40 PFAS in non-drinking water and solid samples such as groundwater, storm water, runoff, landfill leachate, soils, biosolids, biota, and fish tissue (U.S. EPA, 2023c). One testing laboratory company, developed testing to report up to 75 PFAS in drinking water and non-drinking water (Eurofins, n.d.).

Targeted analyses include methods where the chemicals or substances can be quantified and defined. The analyses require chemical reference standards, and methods result in quantified concentrations of a chemical or substance on a defined (or targeted) list. The CDC and U.S. EPA methods mentioned previously are targeted analyses and are limited to the quantification of 40 or fewer specific PFAS. Targeted analyses of PFAS, including those published by the CDC, EPA, U.S. Department of Agriculture, and U.S. Food and Drug Administration (FDA), are conducted by gas or liquid chromatography coupled with tandem mass spectrometry (U.S. EPA, 2023c). The chromatographic methods separate the components within complex samples prior to quantitative analysis by mass spectrometry to determine the presence and levels of targeted PFAS. Reportable results from targeted PFAS analyses can be limited in cases where the sample contains PFAS at concentrations below the method limit of detection. In many applications, samples are first pre-treated by solid phase extraction using adsorbents designed to isolate and concentrate PFAS from potential non-PFAS components. Typical detection limits for PFAS such as PFOA and PFOS in aqueous samples are 1 part per billion (ppb); however, analysts are working to reduce their detection limits to meet the needs of future regulations and decreasing exposure limits. Given the limited availability of analytical standards and standardized methods, the limits of detection may vary greatly across reports.

Non-targeted analyses are methods used to identify chemicals or substances that are not previously known or defined prior to testing. NTAs can identify or potentially identify a substance but quantification is less sensitive compared to targeted analyses. High resolution mass spectrometry can be used for screening of known (previously characterized) PFAS and to identify unknown compounds (based on high resolution accurate mass measurements of molecules). The researchers who first identified HFPO-DA used this approach (Sun et al., 2016). One advantage of NTA is the generation of large datasets for a given sample that can be retrospectively interrogated for new PFAS of interest later. Given the existence of thousands of PFAS and lack of analytical standards for each, these types of analyses are advantageous but require extensive data processing, have limited sensitivity compared to targeted analyses, and require expensive, sophisticated instrumentation that is not available in all laboratories.

Additional non-targeted screening approaches intended to serve as indicators for total PFAS include total fluorine and TOF analyses. Total fluorine analysis detects both inorganic and organic fluorine within a sample, whereas TOF methods, such as adsorbable organic fluorine for liquids and extractable organic fluorine for solids, provide better estimates of total PFAS in a sample. Total fluorine may be quantified with several approaches, including combustion ion chromatography, particle-induced gamma-ray emission spectroscopy, instrumental neutron activation analysis, and fluorine-19 nuclear magnetic resonance spectroscopy. Overall, as the number of PFAS identified increases, there is a continual need to develop and validate analytical methods that can quantify those chemicals in various media. **Table 2-1** summarizes current methods published by federal agencies.

Table 2-1. PFAS Testing Methods in Biological Matrices, Environmental Media, and Products

Agency	Method	Matrix	Number of PFAS Analyzed or Type of PFAS Indicator
Targeted Analyses by LC-MS/MS			
CDC	Method 6304.09	Human Serum	9
USDA	CLG-PFAS 2.04	Bovine, porcine, poultry, and *Siluriformes* muscle; bovine plasma	16
U.S. EPA	Method 533	Drinking Water	25
U.S. EPA	Method 537.1	Drinking Water	18
U.S. EPA	Method 8327	Groundwater; surface water; wastewater	24
U.S. EPA	Method 1633 *(Draft)*	Non-potable water; soil; biosolids; biota; fish tissue	40
U.S. FDA	C-010.02	Food	16
Non-targeted Analyses			
U.S. EPA	Method 1621 *(Draft)*	Water	Absorbable Organic Fluorine
U.S. EPA	*(In Development)*	Environmental	TOF
U.S. EPA	*(In Development)*	Environmental	Total Organic Precursors

Notes: LC-MS/MS = liquid chromatography coupled with tandem mass spectrometry; CLG = Chemistry Laboratory Guidebook.

2.2 White Paper Objectives and Structure

The purpose of this white paper is to provide an overview of PFAS, particularly as PFAS relate to consumer products. The objectives of the white paper include the following:

- **Product Use:** Index current and potential uses of PFAS in general consumer products and children's products;
- **Lifecycle:** Describe the lifecycle of PFAS and PFAS-containing products from initial production from raw materials to waste management;
- **Market Trends:** Assess market trends related to the supply and demand of PFAS and PFAS-containing products both domestically and internationally;
- **Regulations:** Summarize key local, state, federal, and international regulations enacted or proposed on PFAS;
- **Alternatives:** Identify current and potential alternatives for PFAS in consumer products;
- **Exposure and Risk:** Index key sources of PFAS exposure assessments and risk assessments; and
- **Health Effects:** Summarize the current state of science related to human health effects associated with PFAS exposure, including both cancer and noncancer health outcomes.

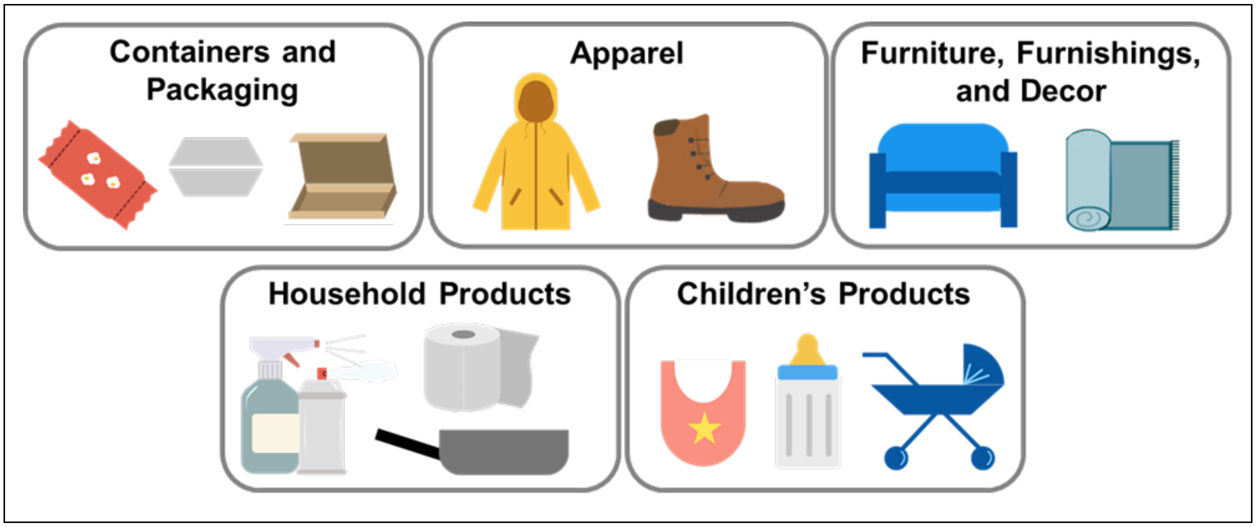
The white paper provides an overview of methods in Section 3, results in Section 4, a discussion in Section 5, uncertainties and limitations in Section 6, recommendations and next steps in Section 7, a brief conclusion in Section 8, and references. Supplemental information is available in the separate appendices document. Results related to PFAS in consumer products are overviewed in **Section 4.1**, while market trends for PFAS are detailed in **Section 4.2**, regulatory trends and alternatives in **Section 4.3**, and potential exposure and human health risks are summarized in **Section 4.4**.

3. Methods

3.1 PFAS in U.S. Consumer Products

Methods were developed to identify known uses of PFAS in all types of consumer products within the jurisdiction of the Consumer Product Safety Commission (CPSC), in addition to materials that are reasonably similar to, or related to, consumer products in CPSC's jurisdiction. **Figure 3-1** shows key consumer product categories that commonly contain PFAS and are used in and around the home, schools, and recreational settings.

Figure 3-1. Common Consumer Products with PFAS



Using internal expertise and information, literature reviews, patents, and publicly available datasets, known, suspected, or potential PFAS in consumer products were summarized for this paper. In addition to identifying known uses in consumer products and summarizing the available information, efforts were made to characterize patterns of use, regulatory landscape, potential exposure routes, and human health effects. Materials that have been and continue to be incorporated into consumer products, their production, and lifecycle information were also summarized. Methods are briefly described in the following sections with additional details in **Appendix A**.

General-use products are consumer products that are not designed or intended primarily for use by children 12 years of age or younger.

A subset of general-use products are children's products. A "children's product" is defined as a consumer product designed or intended primarily for children 12 years of age or younger. Children's products are subject to a set of federal safety rules, called children's product safety rules.

3.1.1 Consumer Product Classification

Unified product categories were developed such that categories could be used consistently across white paper topics and database development, and to facilitate future decision-making by CPSC. Products and materials were primarily classified on the basis of public-facing categories available on CPSC webpages (Consumer Product Safety Commission, n.d.-a; CPSC, n.d.-c), RTI's professional judgement on related products or materials that could contain PFAS, and direct consultation with CPSC staff.

Product categories from CPSC's webpages were slightly modified and grouped under three overarching categories:

- *Higher Priority Consumer Products, or Products Adjacent to CPSC Jurisdiction* applies to product categories that are likely to have PFAS-containing consumer products either under CPSC's jurisdiction or not directly under CPSC's jurisdiction.
- *Non-Consumer Products or Materials* applies to categories that are not related to consumer products but that may be relevant for characterizing aspects of PFAS (e.g., PFAS lifecycle, human exposure).
- *Supplemental Products and Materials* applies to products or materials that are not likely to be common sources of PFAS and/or are not typically considered consumer products.

Product categories—and illustrative examples—are provided in **Table 3-1**. However, select topics used more granular product subcategories in conjunction with the broader product categories presented below.

Table 3-1. Product Categories

Product Category	Primary U.S. Jurisdiction(s)	Examples
Higher Priority Consumer Products, or Products Adjacent to CPSC Jurisdiction		
Childcare Products	CPSC; NHTSA	car seat, infant carrier, crib, stroller, pacifier, other care products intended for use by children <12 years old
Clothing, Apparel, Jewelry, and Accessories	CPSC; Federal Trade Commission	jacket, shoes, boots, stain/water-resistant fabric, uniforms, textiles, personal protective equipment, menstrual underwear
Containers and Packaging	CPSC; FDA	food packaging, fast food wrapper, grease-resistant paper, pizza box, general containers or packaging, child-resistant packaging
Cosmetics and Personal Care Products	FDA	sunscreen, eye makeup, deodorant, shampoo, dental floss, nail polish
Electronics	CPSC	smart technology screens with anti-fingerprint screen
Food Products	FDA; USDA	meat, poultry, produce, seafood, shelled eggs, processed eggs, packaged food products
Furniture, Furnishings, and Décor	CPSC	mattress, pillow, upholstered furniture, curtains, candles, carpeting, flooring, rugs, upholstery, other home textiles
Household Products	CPSC	household cleaning products, dishwasher detergent, household paint, fabric treatments, nonstick cookware
Infant Formula	FDA	–

(continued)

Table 3-1. Product Categories (continued)

Product Category	Primary U.S. Jurisdiction(s)	Examples
Outdoors, Outdoor Recreation, Sports, and Fitness	CPSC	ski wax, crumb rubber, camping tent, umbrella
Small and Large Appliances	CPSC	kitchen appliance with anti-fingerprint and/or nonstick coating
Toys, Hobbies, and Crafts	CPSC	infant and children's toys, children’s crafts, adult indoor hobby products, adult craft materials
Non-Consumer Products or Materials		
Industrial Product or Material	OSHA; EPA	construction materials, aqueous film-forming foams (AFFFs), ink, lacquer, lubricant, adhesive, sealant, industrial coating, plastic manufacturing aid, rubber manufacturing aid, oil and gas processing aid, other industrial processing aid
Manufacturing Product or Material	OSHA; EPA	materials noted or suspected as currently or historically incorporated into consumer products
Recycled Product or Waste	EPA	e-waste, solid waste materials, recycled materials
Supplemental Products and Materials		
Controlled Items	Bureau of Alcohol, Tobacco, Firearms and Explosives; FDA	firearms, ammunition, tobacco, tobacco products
Medical Products	FDA	drugs, over-the-counter medications, medical devices, tests, bandages, veterinary medicines, dietary supplements (vitamins and herbal products)
Miscellaneous Household or Industrial Products	CPSC; USCG; OSHA; EPA; FDA	fuel, lighters, fireworks, kitchen appliances, lawnmowers, bicycles, pools/spas, batteries, magnets, boats, pesticides/fungicides, disinfectants, agricultural product, pet foods and livestock feeds, electronic products emitting radiation (e.g., microwaves)

Notes: CPSC = Consumer Product Safety Commission; NHTSA = National Highway Traffic Safety Administration; OSHA = Occupational Safety and Health Administration; USCG = United States Coast Guard

In addition to these product categories, throughout the white paper, products may be referred to as “general consumer products” or “children’s products” based upon the following definitions used by CPSC:

- General-use products are consumer products that are not designed or intended primarily for use by children 12 years of age or younger.

- Children's products are consumer products designed or intended primarily for children 12 years of age or younger, and therefore, subject to a set of federal safety rules–children's product safety rules.

3.1.2 The Universe of PFAS

Publicly Available Datasets

PFAS List. Given the ongoing scientific debate on what chemicals are considered PFAS (see **Section 2.1.2**), a comprehensive list of PFAS was compiled using lists published in the U.S. EPA's CompTox Chemicals Dashboard,[1] the Toxic Substances Control Act (TSCA) list of PFAS (introduced in 2021), and the Toxics Release Inventory (TRI) list of PFAS (updated in January 2023). By compiling these lists, we identified 16,229 PFAS for our master list referenced throughout this white paper.

Given the number of PFAS in the master list, only a subset were categorized according to the chemical structure categories described in **Section 2.1.2** and are listed in each of the database files described in **Section 3.4**. The chemical structure categories were determined by assessing available chemical structures and leveraging the categorizations provided by OECD (OECD, n.d.-a). Substances that did not fit into one of the structural group categories defined in **Table 3-1**, were either binned at the class or subclass level (e.g., perfluoroalkyl substances, polyfluoroalkyl substances, or polymers) or considered "undetermined."

PFAS in Consumer Products Database. The database for consumer products that use or may contain PFAS was compiled from several publicly available datasets (*PFAS Source Characterization Database.xlsx*). Data reported within literature sources were not extracted for inclusion in the database. However, the electronic supplementary information from one literature review and one overview on PFAS uses were included (Glüge et al., 2020; Gaines, 2023). The two were included because of the extensive search methods used (i.e., use of chemical data reporting, databases, industry webpages, market reports, patents, and peer-reviewed articles), presence of readily available data in the electronic supplementary information as Microsoft Excel spreadsheets, and relevancy in publication within the past couple of years.

With respect to datasets, inclusion was based upon data granularity (i.e., concentration whether qualitative or quantitative, specific consumer product names, etc.) and whether the data could be exported in a usable format. The following datasets were selected for inclusion: ChemSec PFAS Guide, Food Packaging Forum Food Contact Chemical Database (FCCdb), High Priority Chemicals Database (HPCDS), U.S. EPA's Chemical and Products Database (CPDat), and U.S. EPA's Chemical Data Reporting (CDR) Database from 2006 (when named the Inventory Update Reporting), 2012, 2016, and 2020.

Across the datasets, data granularity varied. For instance, CDR was the only dataset to specify whether the product was specifically used in a child's consumer product, whereas CPDat was the only data set to report specific brand names and products. Where possible, our database carried that data granularity forward in the compilation of datasets. Therefore, the database included the following variables: Chemical ID, Chemical Abstracts Registry Number (CASRN), DSSTox Substance Identifier (DTXSID), Accession Number, Chemical Name, Product

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[1] The CompTox Chemicals Dashboard is a publicly available online tool that integrates available chemical information including physicochemical properties, environmental fate and transport, exposure, usage, in vivo toxicity, and in vitro bioassay. Data are compiled from sources including the EPA's computational toxicology research databases, and public domain databases such as the National Center for Biotechnology Information's PubChem database and EPA's ECOTox Knowledgebase.

Category, Product, Used in Children's Products, Concentration Category, Source Dataset, and Additional Notes.

Patent Review. Patent literature provides an additional lens to complement other research streams and can be leveraged to help determine potential consumer products containing PFAS. However, it is important to note that mentioning PFAS in a patent does not confirm its use in a final consumer product. Additionally, patents that do not specifically mention PFAS could still include PFAS in a final consumer product. Several companies may protect their ideas or inventions by keeping product or process details as trade secrets, rather than filing a patent that will be publicly available. While patents cannot provide a definitive answer as to whether PFAS are present in a product, they can provide insights on whether organizations have considered the use of PFAS. These insights can be derived through review of patent documents by identifying consumer products or applications that either discuss the use of PFAS or discuss replacing PFAS.

We conducted a search of patent literature using PFAS terms and keywords derived from the overarching consumer product categories (**Table 3-1**). Additionally, to narrow and simplify the patent set, we only captured documents published between 2000 and 2022 and reduced the set so that only one patent was identified from each simple patent family.[2] This initial strategy provided directional indications around which products were more likely to contain PFAS, but the size of the patent set was unmanageable, returning over 400,000 patent documents. Summary results are shown in **Appendix B**.

To further reduce the number of resulting patent documents, we refined the search strategy by leveraging the Cooperative Patent Classification (CPC) system[3] to target patents specifically related to consumer products and to reduce the noise of irrelevant patents. Relevant CPC codes, at the class, subclass, or group level were selected based on their relevancy to consumer product categories of interest. The final search strategy included 31 CPC codes.

The associated patents were aggregated into the database (*PFAS Source Characterization Database.xlsx)* for further review and analysis. However, there was still some noise as not all resulting patents were relevant to consumer products. Therefore, for each product category, illustrative examples were selected for summary based on expert opinion with consideration of popular consumer products in the marketplace.

Targeted Literature Searches

Targeted literature searches were not limited to certain types of literature sources (gray literature, government reports, peer-reviewed articles, etc.) or search platforms. However, systematic reviews and other high-quality summary documents were prioritized for retrieval and review. Initial search terms included general chemical terms, specific legacy chemical terms (i.e., "perfluorooctanoic acid" and "perfluorooctanesulfonic acid"), and topical terms. The searches were an iterative process wherein search terms were refined based on results.

PFAS in Consumer Products. Given that patents span beyond consumer products (patents can pertain to component parts, designs, methodologies, processes, etc.), a targeted literature search was conducted to supplement the results of the patent review. Topical terms for the searches included the product categories in **Table 3-1**. Additionally, results from the searches and screens of Tier 2 evidence (see **Section 3.3**) supplemented this information.

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[2] A simple patent family is a set of patent documents that relates to a single invention.

[3] The CPC system is the patent classification system adopted by the European Patent Office (EPO) and U.S. Patent and Trademark Office in 2013. Patents published prior to 2013 have been updated to be classified by this system.

Lifecycle Information. Lifecycle information, including the potential breakdown of materials over time and use of recycled materials that may contain PFAS, was considered of interest to understand human exposure to PFAS. Specifically, the following lifecycle information was prioritized: 1) potential for breakdown of materials over time and 2) consumer products made from recycled materials that are known to contain PFAS. Targeted literature searches were conducted to better understand the current state of the science and identify data gaps. Topical terms for the searches included “breakdown,” “consumer behavior,” “degradation,” “disposal,” “end of life,” “weathering,” and others.

In addition, information on PFAS as potential byproducts, contaminants, or impurities throughout the lifecycle process was of interest. We sought to further understand what PFAS may be present as byproducts or precursors during production or as impurities from another production process. Topical terms for the searches included “byproducts,” “degradation products,” “contaminants,” “impurities,” and similar terms.

Select Interviews for Expert Elicitation

Data gaps were expected across the objectives of this white paper. Therefore, interviews to elicit expert opinions were conducted after the patent review and literature searches were finalized. We contacted 12 different organizations that spanned expertise across consumer product categories and value chain, including academics researching alternatives, consumer product formulators, industry experts in plastics and plastics processing or textiles, and experts at nongovernmental organizations. Based on responses, six interviews were conducted and five were included in this white paper. One interview was omitted due to the quality of the interview; additional knowledge was not provided on PFAS and their use throughout consumer products and industry. All affiliations and names of the experts are undisclosed.

Interviews helped to understand the presence of PFAS in consumer products whether from intentional or unintentional addition, industry perspectives, and any key challenges in the transition to a PFAS-free marketplace. The interview guide used is in **Appendix A**. In the cases where individuals declined interview requests, the expert judgement of our RTI team, including Dr. Jamie DeWitt, characterized the data gaps and needs.

Additionally, the Paperwork Reduction Act requires federal agencies to obtain approval from the Office of Management and Budget before posing identical questions to 10 or more people or entities. Subsequently, RTI communicated with CPSC staff on the development of potential interview question sets and interviewees to ensure compliance with the Paperwork Reduction Act.

3.2 PFAS Commodity Market Trends

We characterized trends in spatial and temporal patterns, within the United States and globally, and over the past decade in PFAS production, use, and regulation. We aggregated PFAS into three categories throughout our methods: perfluoroalkyl substances, polyfluoroalkyl substances, and polymers. Our methods were designed to characterize the scale and trends of the overall PFAS commodity market in terms of observable domestic production, international trade, and potential direct uses.

3.2.1 Supply and Demand Characterization

To characterize the overall scale of the PFAS commodity market and spatial distribution, we identified domestic PFAS-producing facilities, PFAS import and export volumes by port, and direct PFAS-using sectors. Our methods best capture potential PFAS exposures in the initial production, import, and sale of PFAS in their chemical form. To further characterize potential PFAS exposures, we supplement our producer and direct-user identification with reported TRI releases of PFAS, which may come from producers, consumers, waste management sites, or other facilities.

The end-products of our supply and demand characterization include a database (*PFAS Commodity Market Trends Database.xlsx*), tables and figures, and an interactive map (RTI, 2023) reporting the following PFAS data for the United States:

- *Producing facilities* with location, sector, and other attributes (when reported),
- *Production volume* by PFAS categories and sectors (estimated),
- *Import and export volumes* by PFAS categories, ports of entry, and countries of origin (when reported),
- *Consumption volumes* by potential direct PFAS-using sectors (estimated), and
- *Releases reported* from any facility type by industry, PFAS category, and reporting year.

PFAS-Producing Facilities. We identified a list of domestic PFAS-producing facilities using the U.S. EPA's CDR datasets. The CDR rule, under the TSCA, requires U.S. facilities that are producing (manufacturing or importing) certain chemicals to report information to the EPA every four years. This information provides the best publicly available data on chemical production in the United States and is used by the U.S. EPA to characterize PFAS production. Reporting is only required when production volumes were at least 25,000 pounds for most chemicals and 2,500 pounds for some chemicals. Using the comprehensive list of 16,229 PFAS described in the previous section, we identified a total of 1,410 PFAS listed on the TSCA inventory of chemicals, of which 557 PFAS met the lower reporting threshold (including PFOS and PFOA). Only data that are not classified as confidential business information (CBI) are publicly accessible.

A total of 150 PFAS-producing facilities, including both manufacturers and importers, were identified from the 1998–2020 CDR datasets. A facility's associated industry, designated by a North American Industry Classification System (NAICS) code, was only available for the 40 facilities that reported in the most recent 2020 CDR dataset, as this was a recent requirement. To identify the industry associated with facilities without NAICS codes in the CDR data, the Facility Registry Service IDs or reported Industrial Sector codes were matched to NAICS codes. We linked NAICS codes to an additional 88 facilities, for a total of 128 facilities with industry information. When multiple NAICS codes matched to a facility, all NAICS codes were included.

The 2020 CDR data also include limited information on foreign parent companies associated with the PFAS-producing facilities; however, none of the previous reporting cycles provide this information. Given these limitations, we conducted targeted literature searches to identify foreign PFAS-producing facilities that may be importing PFAS to the U.S. market. The resulting data granularity and type of information that could be extracted were highly variable depending on the source, but at a minimum, included the facility name and country. We were not able to identify any numerical quantity data (e.g., PFAS production volume) for foreign facilities but we were able to characterize the quantity of PFAS imports and exports by country, described in the section below.

Trade Quantities. We reviewed export and import data related to PFAS from the United Nations Comtrade Database (referred to as "UN Comtrade") and USA Trade Online. UN Comtrade provides global annual and monthly statistics by product and trading partner; and USA Trade Online provides cumulative export and import data by port for the United States (United Nations, n.d.; U.S. Census Bureau, n.d.).

To track PFAS imports and exports to and from the U.S. market, we first identified PFAS products using the Harmonized System (HS) of commodity codes.[4] We used the searchable list of HS codes by the Observatory of Economic Complexity to identify HS codes pertaining to the trade of PFAS in their chemical form from 2000 through 2023. We cross-referenced the resulting HS codes with the master PFAS list, which filtered our list to 28 HS codes.

We aggregated export and import data using the PFAS categories mentioned previously: 20 HS codes captured perfluoroalkyl substances, 6 HS codes captured polyfluoroalkyl substances, and 2 HS codes captured polymers. We report a full list of HS codes in **Appendix A**. Export and import data for the 28 HS codes were compiled based on weight (reported in kilograms (kgs.) and converted to pounds (lbs.)) and trade value (USD) at the country-level from USA Trade and UN Comtrade. We relied on USA Trade data, which include port of entry, to establish the spatial patterns of PFAS trade in the United States. We rely on UN Comtrade to identify the time trend of U.S. PFAS imports and exports and the global spatial pattern of PFAS trade.

It was not feasible to identify HS codes pertaining to the trade of PFAS-containing products from 2000 through 2023. Data obtained on PFAS-containing products were not at the level of detail needed to identify an HS code. For instance, carpets and rugs are reported to contain PFAS, but those that do and those that do not are not distinguishable by HS code, which are designed to capture only market-relevant product distinctions (e.g., HS code under Chapter 57, “Carpets and other textile floor coverings,” is 570241: Carpets and other textile floor coverings; woven, [not tufted or flocked], of wool or fine animal hair, of pile construction, made up of wool or fine animal hair). We researched independent lists of products known to contain PFAS but found largely incomplete and *ad hoc* collections of PFAS-containing products as described in **Section 4.1**.

PFAS Domestic Supply. We compiled annual domestic PFAS production volumes from the 1998–2020 CDR datasets. These data contained reported production volumes at the facility-level for each chemical from 2010 through 2020. For each of the three previous reporting cycles (2012, 2016, and 2020), the CDR datasets also included information on manufacturing volumes and import volumes, separately. The reporting cycles align to the manufacturing and importing volumes for one year prior (i.e., 2011, 2015, and 2019), but will be referred to as their reporting year for the remainder of the paper. Many of the facility-level production volumes, manufacturing volumes, and importing volumes were classified as CBI and were not publicly available.

We also created a list of nationally aggregated annual production volume estimates for each PFAS chemical using the CDR National Aggregate Production Volume datasets available for 2012, 2016, and 2020. If CDR did not classify any of the production volumes for a particular PFAS chemical as CBI, then the public CDR database included specific values for the aggregated production volumes for that chemical. However, if CDR classified any of the reported production volumes for a given PFAS chemical as CBI, then CDR provided the aggregated production volumes as a range. We report on the reported minimums and maximums and their midpoints.

We aggregated the facility-level manufacturing and importing volumes to the PFAS category and NAICS code level for each of the years with available data (2012, 2016, and 2020). Our literature, database, and web searches for the facilities with production volumes that reported NAICS codes outside of the 325 (Chemical Manufacturing) sectors suggested that these codes were unlikely to be related to PFAS manufacturing. We therefore selected all NAICS codes

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[4] HS is a hierarchical classification system. The HS codes are updated every five years with editions released in 1996, 2002, 2007, 2012, 2017, and 2022. The new editions may include addition, deletion, and/or modification of codes, descriptions, headings, and standard notes, which may be a result of changes in the trade patterns and/or technological developments.

within 325 with reported manufacturing volumes to define NAICS production in economic data. For analyzing import volumes, however, we included all reported NAICS codes. When a production facility reported more than one NAICS code, we assumed the production volume was split evenly across each industry. We then summed the volume of each chemical by PFAS category and NAICS code. The result of aggregating the facility-level data in this way was an estimate of manufacturing and importing volume by PFAS category and NAICS code for 2012, 2016, and 2020.

The totals resulting from this aggregation form a partial basis for characterizing the domestic supply of PFAS in their chemical form in the U.S. economy; however, CBI renders these aggregates from the facility-level volume totals incomplete. CDR reports only a small fraction of the CDR-reported nationally aggregated annual production volumes at the facility-level—approximately 3% of polymers, 8% of perfluoroalkyl substances, and 17% of polyfluoroalkyl substances are reported at the facility-level using the midpoint of the ranges reported in the nationally aggregated annual production volume totals. Therefore, to estimate *total* domestic production by NAICS code and PFAS category, we used the CDR facility-level production volumes as a representative sample of total production and apportioned the nationally aggregated production volume for each of the PFAS categories to NAICS codes using the facility-level volume shares (i.e., sum of facility-level volumes for a NAICS code and PFAS category divided by total facility-level annual production volumes for the PFAS category). When CDR reported a range for a national production volume, we used the midpoint. The year 2016 was chosen as the benchmark for this trends analysis given that it had the highest percentage of facility-level reporting compared to the nationally aggregated production volume totals.

PFAS Domestic Demand. Next, we characterized PFAS demand by identifying sectors of the economy that are potentially directly purchasing PFAS. We used the list of 110 NAICS codes associated with PFAS-producing facilities and prioritized the NAICS codes associated with facilities listed as manufacturers of PFAS in CDR within the 325 Chemical Manufacturing sector to identify potential direct consumers of PFAS. NAICS codes for importers of PFAS are far too broadly defined (e.g., as “wholesalers”) to form a reliable basis for PFAS supply. Instead, we base our demand index on the pattern of domestic purchases from PFAS-producing NAICS codes.

As production levels from these sectors change, demand for PFAS is likely to change approximately in proportion (e.g., a 10% rise in output from a PFAS-using industry would require it to purchase approximately 10% more PFAS). PFAS production occurs in sectors that produce many other chemical substances, so we cannot be certain that purchases from the PFAS-producing sectors we identified above are actual purchases of PFAS. Instead, we proxy for PFAS demand by identifying all sectors with purchases from PFAS-producing sectors as potential demand sources.

To assess time trends in PFAS production, we use the projected growth of these potential PFAS demand sectors to form a PFAS demand index. We use input-output data from the Bureau of Economic Analysis (BEA) to identify which sectors purchase from PFAS-producing NAICS codes. BEA input-output Accounts Data provide “make” and “use” tables (BEA, 2023) that report the dollar value of production and purchases between sectors within the economy nationally and annually at approximately the 3-digit NAICS level (71 sectors), and pent-annually at approximately the 6-digit NAICS level (405 sectors). The detailed pent-annual data are produced with a 5-year lag; the latest data with a version year of 2022, due to be released in late 2023, will be based on BEA economic surveys conducted in 2017. We rely on the 2017 data release that reports on economic activity as of 2012.

To identify potential direct PFAS-using sectors, we filtered the detailed BEA "use tables" to only include commodities with PFAS-producing NAICS codes (6-digit; identified above). Potential direct PFAS-using sectors are those with dollar value purchases from PFAS-producing sectors. We apportion the physical quantity of PFAS supply from the national CDR data by PFAS category from each producing sector to potential PFAS using sectors proportional to the dollar value of intermediate purchases among the sectors. We then estimate the quantity of potential PFAS category purchases between sectors and the total potential demand for each PFAS category. The result of this analysis is a demand index that we can use to estimate the quantity of PFAS that would be supplied to the U.S. economy based on future projections of gross domestic product and historical output to gross domestic product ratios. Additional information on the equations used to calculate PFAS domestic demand can be found in **Appendix C**.

Reported PFAS Releases. EPA's TRI program requires the reporting of chemical information from industry facilities. We identified facilities reporting PFAS releases using the TRI On-Site Releases dataset. The resulting dataset included the amount of each PFAS category released in pounds by 89 distinct facilities for 2012–2021. These facilities were compared to the PFAS-producing facilities from the CDR dataset to identify which producing facilities also reported PFAS releases.

We also tabulated the reported PFAS releases by PFAS category, reporting year, and industry using the TRI assigned Industry Sector, derived from the NAICS code associated with each facility. The release rate was calculated by dividing the total reported TRI releases for each PFAS category by the total supply of PFAS calculated from the CDR nationally aggregated production volumes.

3.2.2 Spatial Distribution of PFAS Production and Releases

PFAS Supply

We mapped the 150 distinct PFAS-producing facilities according to the latitude and longitude reported in the CDR data. Using the compiled facility-level production volume data described in the "Supply and Demand Characterization" section, we determined the amount of PFAS each facility manufactured and imported for the years 2012, 2016, and 2020 by PFAS category. The manufacturing and importing volumes for all categories were averaged across years to get a total average annual production volume (pounds) for each facility. The maps also provide information on the facility's activity as a manufacturer of PFAS, importer of PFAS, or both and industry type of each facility (using the NAICS code).

PFAS Trade

We used USA Trade data to sum the physical quantity of PFAS imports and exports by port of entry/exit, identified by latitude and longitude. The data were displayed on a map according to port and volume of total PFAS trade (imports plus exports). In a separate map, we used UN Comtrade total reported trade volume (imports plus exports) by country to generate a global choropleth map of countries by total trade volume.

PFAS Releases

We mapped the 89 distinct facilities reporting PFAS releases using the addresses available in the TRI dataset. The releases were summed by PFAS category for each year and averaged for 2012–2020 to get an average annual reported release amount (pounds). Only the years with reported releases were included in the average for each facility.

3.3 PFAS Regulatory Trends and Alternatives

3.3.1 Regulatory Trends

We identified regulations across the United States at the federal, state, and local level, as well as regulations internationally, by searching datasets and websites. The searches were conducted from December 2022 to May 2023.

Federal, State, and Local U.S. Regulations

Current regulatory activities, including bans and restrictions, were reviewed at the federal and state levels of government. The PFAS Team at the Interstate Technology Regulatory Council (ITRC) developed a Microsoft Excel spreadsheet with summary information for the regulation of PFAS at several levels—state and territory programs, federal programs, and international programs starting in 2017 (ITRC PFAS Team, 2022). The spreadsheet was last updated in October 2022, and therefore, we used it to initially identify regulations and guidelines (or policies) related to PFAS.

In addition to the technical resource by ITRC, Safer States, an alliance of diverse environmental health organizations and coalitions, has a bill tracker specific to PFAS. The listing of adopted and current policies was extracted from the Safer States website to contribute to the listing of current regulatory activities at the state level.

Individual searches at the local (i.e., county or city) and state levels were conducted to further determine which states have current regulatory activities that extend beyond those at the federal level. All U.S. regulations were catalogued in a searchable database that can be used to gauge trends over time and filter by primary focus topics and PFAS-containing product category (*PFAS Regulation Index.xlsx*).

Select International Regulations

Regulatory activities at the international level of government were searched to determine current regulatory activities that extend beyond those at the U.S. federal level of government. Among the technical resources developed by the PFAS Team at the ITRC, the international programs represented 10 different locations: Australia and New Zealand, Canada, Denmark, European Union, Germany, Italy, Netherlands, Norway, Sweden, and the United Kingdom.

Additionally, the European Chemicals Agency's (ECHA's) website and OECD's Portal on Per and Poly Fluorinated Chemicals were searched (OECD, n.d.-b). The ECHA website includes news on hot topics, including PFAS, where latest updates are posted on the universal PFAS restriction proposal, restriction proposal on PFAS in firefighting foams, and others. Additionally, the page includes key summary information on PFAS: what are PFAS and what are they used for? What are the concerns? How are PFAS regulated in the EU? In OECD's portal, country information included a summary on recent initiatives and policy approaches for 15 locations: Australia, Canada, China, Denmark, European Union, Finland, Germany, Japan, Korea, Netherlands, Norway, Poland, Russia, Sweden, and United States.

3.3.2 PFAS Substitutes

Data Collection

Expert elicitation and targeted literature searches were used to identify existing and potential PFAS substitutes. The targeted literature searches helped to understand the current state of the science. The searches were not limited to any type of literature source (e.g., gray literature, government reports, peer-reviewed articles) or searching platform. Initial search terms included general chemical terms, specific legacy chemical terms (i.e., "perfluorooctanoic acid" and "perfluorooctanesulfonic acid"), and general terms to encompass the use of alternatives or substitutes. The searches were an iterative process wherein search terms were refined based on results.

PFAS Price Considerations

As part of this effort, we characterized the role price has played on how industry selects PFAS and the degree to which international trade supports or complicates the demand for PFAS in domestically available consumer products. Based on the targeted literature search results on substitutes, we characterized the role that price has played in the selection of PFAS and substitutes, as well as the impact of regulatory and other non-price factors on industrial and consumer use. We also summarized trends in the use of non-PFAS substances and identified examples of common PFAS substitutes.

3.4 PFAS Exposure and Human Health Risks

3.4.1 Literature Review: PFAS Exposure, Toxicity, and Human Health Risk

Sources of Evidence

We identified existing literature to characterize the current state of knowledge on exposure, toxicity, and human health risk to PFAS. Literature sources were compiled using a combination of targeted, online searches and formal literature searches to develop an evidence base of diverse resources related to exposure, toxicity, and human health risk.

We developed a tiered approach for classifying evidence: Tier 1 evidence (highest priority evidence, produced or endorsed by international and domestic government agencies or similarly authoritative sources); Tier 2 evidence (peer-reviewed literature); and Tier 3 evidence (expert opinion and other sources). Tier 1 evidence was compiled until May 2023, while Tier 2 evidence was searched between January 2000 and January 2023. Separate searches were conducted for Tier 2 evidence: one focused on exposure and completed exposure assessments and the other focused on toxicity and risk assessments. Further details including search strategies for Tier 1 and Tier 2 evidence are available in **Appendix A**.

Screening of Evidence

The web-based software application SWIFT-Active Screener (Sciome, LLC, Research Triangle Park, NC) was used to screen the Tier 1 and Tier 2 evidence. The application is used for collaborative work on systematic reviews with behind-the-scenes "active learning" and statistical models to prioritize references considered relevant. Given the differences in search strategies, the active learning models were only used for Tier 2 references.

Review of Tier 1 Evidence (Highest Priority—Government Agencies or Authoritative Sources)

All references were first screened at the title-abstract level for general relevancy and to tag basic information about the resource. Resources deemed relevant were then screened and tagged at the full-text level to characterize more detailed attributes about the resource. Tagging fields included available information such as resource type, PFAS included, population characteristics, study design, exposure matrices, health endpoints, any identified links to consumer products (using product categories defined in **Section 3.1.1**), and available quantitative health-related information. Not all tagging fields applied to all resources.

Review of Tier 2 Evidence (Peer-Reviewed Literature Sources)

We used SWIFT-Review (Sciome, LLC) to aid in the prioritization and conceptualization of the Tier 2 evidence compiled from the literature searches.[5] We manually annotated a set of approximately 200 references in each bin (one bin for exposure and one bin for toxicity and risk) of Tier 2 literature searches to denote them as either “Include” or “Exclude.” These training sets were imported to SWIFT-Review to use in the platform’s prioritization algorithm. This algorithm ranks articles by a predicted relevancy score; articles that ranked above the lowest ranked, manually annotated article were included in the smaller subset of highly relevant references from the Tier 2 literature sources.

The final subset of highly relevant Tier 2 resources were then reviewed and tagged using SWIFT-Active Screener’s “active learning” model with screening limited to a 95% inclusion threshold (Howard et al., 2020). Tier 2 evidence was screened and tagged using the same fields as Tier 1 evidence to ensure consistency and facilitate direct comparisons among resource types within the database (*PFAS Literature on Exposure, Toxicity, and Health Risk.xlsx*).

3.5 Database Development and Documentation

RTI developed a database and supporting documentation for data and information acquired on four overarching topics: 1) consumer products, 2) market trends for PFAS chemicals, 3) regulations on PFAS and PFAS-containing products, and 4) PFAS exposure and human health risks. Based on these topics, four different files are available with the data acquired:

- PFAS Source Characterization Database
- PFAS Commodity Market Trends Database
- PFAS Regulation Index
- PFAS Literature on Exposure, Toxicity, and Health Risk

Detailed information on the data in each file can be found on the first tab of each file labeled as “ReadMe.”

Development of the database was conducted in R version 4.1.2 (R Core Team, 2021) to compile, clean, and merge the various data sources. The output from the processes in R resulted in individual Microsoft Excel spreadsheets that were combined and formatted to form the Microsoft Excel files. For consistency and transparency throughout the database, each of the individual tabs included basic identifying data on the specific PFAS (DTXSID, CASRN, chemical name, etc.) and source of the data. A data dictionary was also included to define relevant acronyms, terms, and variables used throughout the database.

Regarding sources of the data, it was assumed that the primary authors of the data already conducted their own quality assurance and control; therefore, the sources were not thoroughly checked for accuracy. However, the authors of the data sources were considered when choosing to include data. Data maintained or produced by U.S. governmental agencies and peer-reviewed journal articles were considered applicable and of high quality.

3.6 Quality Assurance/Quality Control

RTI is committed to providing CPSC with high-quality deliverables. Our document deliverables were subjected to expert editorial review for spelling, grammar, punctuation, acronym use,

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[5] SWIFT-Review uses statistical text mining and machine learning to support prioritization and visualization of large evidence bases. The platform has well-documented search strings from which it derives its automatic tagging categories and subcategories of interest to environmental health researchers (Sciome, 2023).

consistency, tone, style, organizational structure, and logical flow based on established style guides and client specifications. Additionally, our editors checked references, highlighting information gaps, and ensuring consistency within documents written by multiple authors.

4. Results

4.1 PFAS Sources in Consumer Products

The following sections overview why PFAS are useful, particularly in consumer products, and illustrate how prevalent PFAS are in everyday products ranging from cookware to stain-resistant rugs. Additionally, we provide an overview of the lifecycle of PFAS, illustrating human and environmental exposures to PFAS from initial production to disposal.

KEY POINTS

- Several sources from the U.S. EPA were compiled to form a list of 16,229 distinct PFAS for this white paper. We acknowledge that other reviews may have different numbers of PFAS given the debate on definitions for PFAS.
- 28,229 patents were identified with potential information on PFAS use in consumer products. Functional uses include friction reduction, grease/oil repellence, stain resistance, and waterproofing.
- Consumer products may intentionally contain PFAS as an addition for a specific functional use or as a byproduct, impurity, or contaminant from the manufacturing process.
- Users may be exposed to PFAS throughout the lifespan of the PFAS-containing consumer product as the product degrades and weathers.
- Disposal of PFAS results in contamination of biosolids, compost, other soil amendments, and water used for agricultural operations. Composting of food packaging and food waste has been cited as contributing to PFAS contamination of soil amendments.

4.1.1 Applications of PFAS in Consumer Products

Patents

The number of patent families identified for each of the 31 Cooperative Patent Classification (CPC) codes relevant to consumer product categories are shown in **Table 4-1**. Overall, 28,229 patent documents resulted from the searches. Notably, the CPC code C09D for coating compositions had significantly more patent documents than any other category because PFAS are commonly used as coatings or in coating formulations due to their unique properties. Across all the other consumer product categories, cosmetics and personal care products show more than 10,000 patent documents across all the relevant CPC codes.

Other notable categories included the subclasses for cleaning products and detergents (C11D) and fabric treatments (D06M), which had a significant number of patent results with 2,392 and 4,386 documents, respectively. Further evaluation of these patent sets was used to determine the relevancy of the invention. For example, patents in C11D could contain inventions describing either detergents composed of fluorinated compounds or detergents used to clean or remove fluorinated compounds, with the former being of interest.

The following sections summarize what patents currently list PFAS and their use according to the consumer product categories in **Table 4-1**. However, patents related to infant formula were not captured because the patents identified did not indicate that PFAS was used in the formula, and fluorine is only added as a nutrient. In cases where there was a significant number of patent families identified, additional analyses were conducted to further understand what products were represented. In the case of CPC classes, the top percentages of subclasses were analyzed. If a single subclass was dominant (i.e., above 50% of the class), then the top percentages of the groups were analyzed. These analyses were completed for the following consumer product categories: clothing, apparel, jewelry, and accessories; containers and packaging; electronics; food products; household products; and outdoors, outdoor recreation, sports, and fitness.

Table 4-1. Cooperative Patent Classification (CPC) Codes Relevant to High Priority Consumer Product Categories and Resulting Patent Families

Consumer Product Categories	CPC Code	Number of Patents Families Identified
Childcare Products	A47	2,310*
	A61J	396
	B62B	57
	B60N	99
	Total	*2,862*
Clothing, Apparel, Jewelry, and Accessories	A41	1,141
	A43	326
	A42B	73
	A44	211
	A45B	33
	A45C	96
	Total	*1,880*
Containers and Packaging	B65D	2,147
Cosmetics and Personal Care Products	A61Q	5,957
	A61K 8/00	6,530
	A46B	145
	A41G	63
	C11D	2,392
	A45D	322
	Total	*15,409*
Electronics	H04N	927
	H04M	265
	H04W	205
	H04R	553
	Total	*1,950*
Food Products	A23L	1,375
Furniture, Furnishings, and Décor	A47	2,310*
	B68G	15
	C04B	4,645
	Total	6,970
Household Products	A47	2,310*
	C09D	26,362
	D06M	4,386
	D06L	177
	Total	*33,235*
Infant Formula	A23L 33/40	87*
	A23C	107
	Total	*194*
Outdoors, Outdoor Recreation, Sports, and Fitness	C08L 2555/34	4
	C09G	460
	A45F	41
	E01 C13/00	64
	Total	*569*
Small and Large Appliances	A47	2,310*
Toys, Hobbies, and Crafts	A63	648

*Patents may be duplicated across other consumer product categories due to related CPC codes

The purpose of PFAS was largely for its friction reduction, grease and oil repellence, nonstick properties, stain resistance, and waterproofing. However, there were also unique properties described in the patents, including the unexpected ability to increase sun protection factor (SPF) values for cosmetics. Note, that the search strategy still resulted in patents discussing “PFAS-free” ideas or inventions, which is important in identifying what consumer products may have previously contained PFAS and what future consumer products may be PFAS-free. Additional details for the patent examples related to many of the categories described below are reported in **Appendix B**.

Childcare Products. The CPC codes used for childcare products sought to capture any products that were specifically made for children, including domestic articles and furniture. Potential PFAS-containing products explicitly used for infants, toddlers, and/or children included patents for baby bottles. Those patents were focused on different purposes for the bottles. For example, while some patents were categorized as general feeding bottles, others were categorized for specific pharmaceutical or therapeutic purposes. Bottles related to feeding used fluoropolymers and fluororesins for increased impact resistance or as a lubricating agent, whereas bottles/containers for pharmaceutical or therapeutic purposes used fluoropolymers as an inert barrier between pharmaceutical drugs and other materials. For instance, one patent was used for therapeutic purposes as a feeding device, wherein PFAS provided acid resistance relative to the acidity of a patient’s stomach to make it safe for use. Patents with specific relevance to children’s car seats were not identified in the search.

> In addition to baby bottles, childcare products with PFAS patents include water-repellent nap mats and textiles for car sets, for example.

Clothing, Apparel, Jewelry, and Accessories. Several CPC codes pertained to clothing, apparel, jewelry, and accessories. For the CPC class A41 pertaining to wearing apparel, shown in **Figure 4-1**, the majority (83%) of patents were among the subclass of outerwear, protective garments, and accessories (i.e., gloves). The remaining subclasses did not exceed 10% individually. The next largest subclasses included shirts, underwear, baby linen, and handkerchiefs (8%), and artificial flowers, wigs, masks, and feathers (5%). The subclasses for corsets/brassieres and methods for making clothes each made up 2% of the patents in this class.

Further analysis of the patents related to outerwear (**Figure 4-2**) revealed that the categories for professional, industrial, or sporting protective garments (37%) and material specially adapted for outerwear (20%) comprised over half of the inventions in this subclass. The next largest groups, which comprised an additional quarter of the subclass, were garments (14%) and gloves (14%).

Reviews of patents that fall into this consumer product category show that for most apparel and footwear, PFAS have been incorporated as a coating or layer to provide water repellency and antifouling/staining properties. In addition to stain-resistant garments and waterproof boots, the addition of PFAS is proposed for undergarments such as reusable menstruation underwear to provide a water-repellent and dry surface (US20150290049 A1).

The largest contribution of patents to the footwear class (A43; not included in the above exhibit) is from characteristic features of footwear/parts of footwear (89%). Examples of that subclass include comfortable booties and shoe inserts, fireproof footwear, sports shoes with good damping effect (meaning it reduces the vibrations), and others. The other footwear subclasses contributing to 6% of patents include machines, tools, equipment, or methods for manufacturing or repairing footwear with the remaining subclass of fastenings or attachments to footwear contributing 5% of footwear patents.

Figure 4-1. Percentage of Patents per Cooperative Patent Class for Apparel (A41)

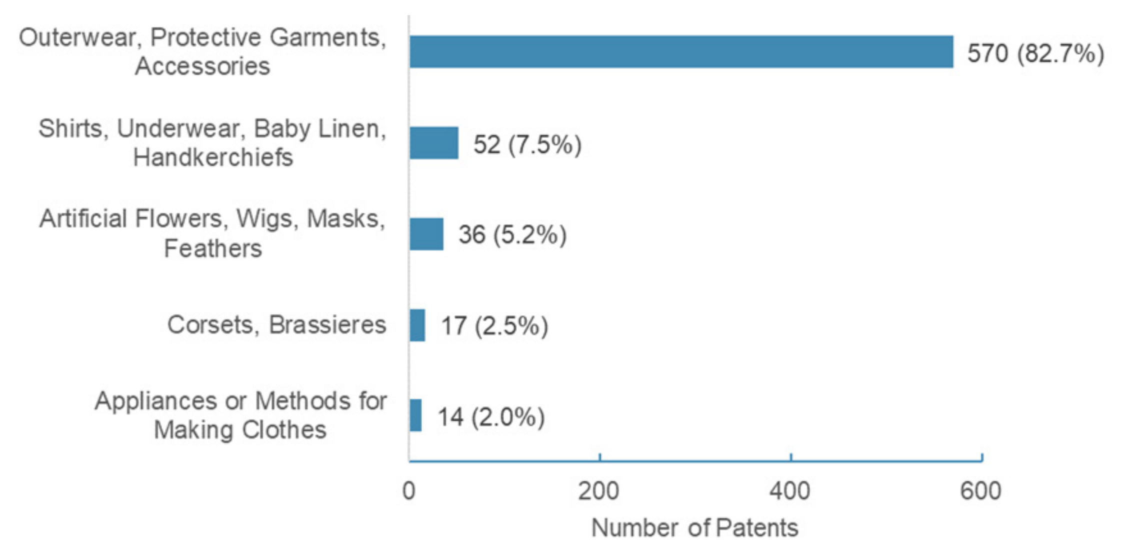
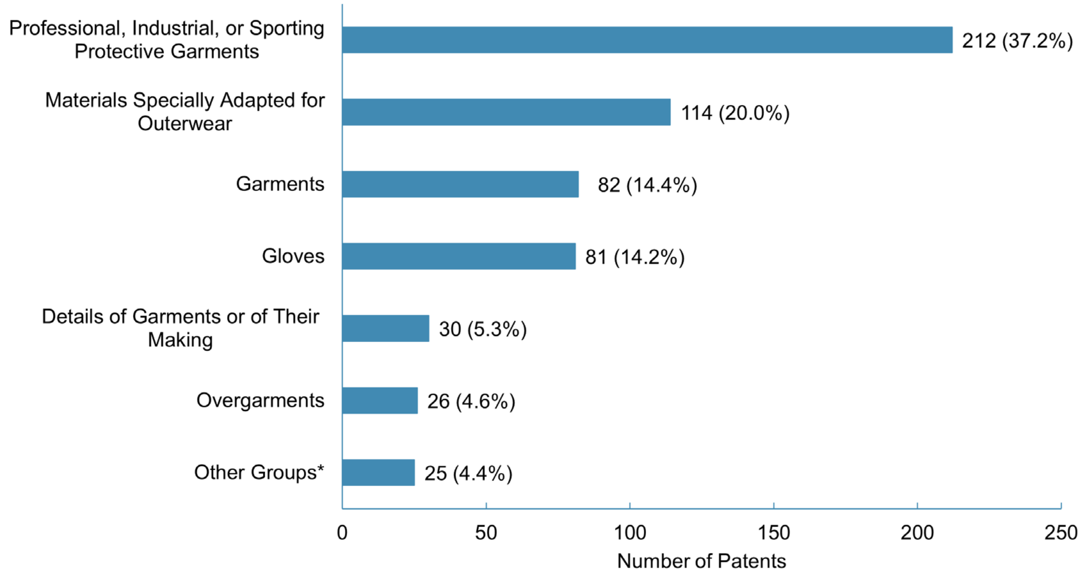


Figure 4-2. Percentage of Patents per Cooperative Patent Subclass for Outerwear



Note: “Other groups” refers to those that contributed less than 1% individually.

The few examples for hat and head coverings (CPC code A42B) described protective wear with PFAS added to aid in the filtration of particles or as a low-friction layer used between polyurethane foam in helmets. Similarly, few examples were seen for jewelry and accessories. However, there were examples of PFAS used in watch bands to provide a silky comfortable feeling (US20180273675 A1). Among accessories, including purses, handbags, and carried bags (CPC code A45C), the examples described the use of PFAS for lunch boxes and an electronics case.

Notable examples for patents on jewelry and accessories include PFAS used in watch bands to provide for comfort (US20180273675 A1) and PFAS use in lunch boxes and electronics cases (CPC Code A45C).

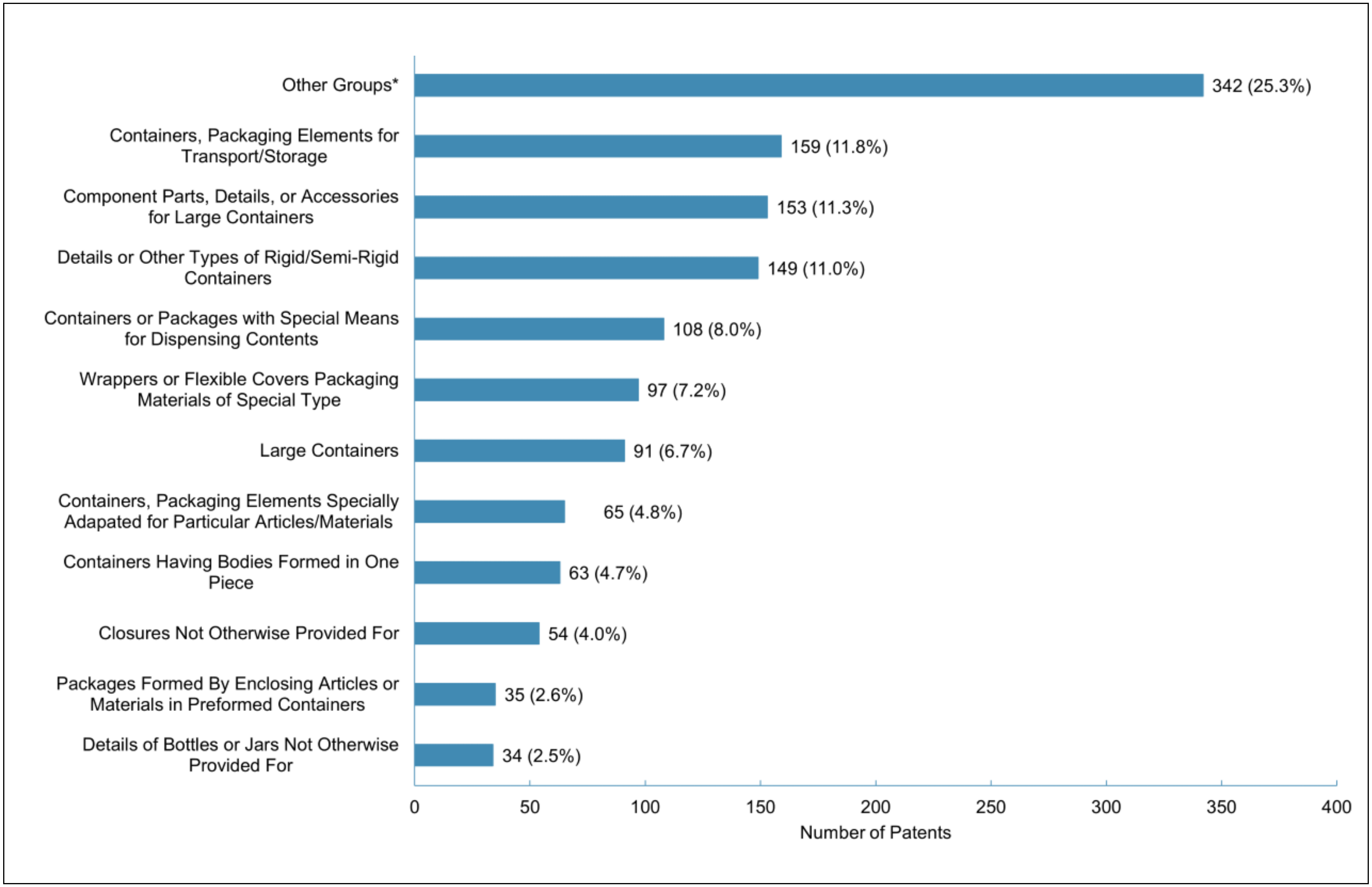
Containers and Packaging. Patents pertaining to containers for storage or transport included several different groups; the subclass of containers was not dominated by a single type (**Figure 4-3**). Specifically, containers, packaging elements, or packages for contents presenting transport or storage problems comprised 12%; component parts, details, or accessories for large containers comprised 11%; while details of other kinds or types of rigid or semi-rigid containers comprised 11% of patents. The next three largest types of containers or packages included special means for dispensing contents (8%), wrappers of flexible covers (7%), and large containers (7%).

Examples of patents summarized in **Figure 4-3** include bag-in-containers with a coating layer, containers with recycled plastic, folding corrugated cartons, treated paper products, and others. These examples are related to carrying/storing beverages and food products with reported use of fluoropolymers and other fluorinated substances primarily for grease, oil, and water repellence. Other uses of fluoropolymers included providing a bacterial barrier, use as a lubricant, and use as a thermoplastic (which enables flexibility upon cooling or heating).

Additional patents revealed that other containers and packaging are specifically reported to be PFAS-free (i.e., microwave popcorn bag [US20210086976 A1] and composite materials for food contact applications [US20170267433 A1]). These are potentially indicative of companies/industries working to differentiate their products from competitors by having similar products but without intentional PFAS use.

- **Containers and Packaging.** Many patents are related to carrying/storing beverages and food products with reported uses of PFAS for grease, oil, and water repellence.
- **Cosmetics and Personal Care Products.** PFAS use in cosmetics and personal care products aid with oil and water repellence like other products but is also uniquely used to increase SPF values.
- **Electronics.** Patents reveal the use of PFAS in electronics to help reduce smudging and stains, repel water, and help with sealing.

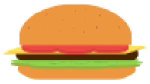
Figure 4-3. Percentage of Patents per Cooperative Patent Subclass for Containers (B65D)



Note: “Other groups” refers to those that contributed less than 2.5% individually.

Cosmetics and Personal Care Products. Patents related to cosmetics and personal care products include brushes and sponges for makeup application and different cosmetic compositions. PFAS use among these products varies. The patent entitled ‘Brush for applying substance to eyelashes and/or eyebrows’ (US20040168698 A1) described the use of PTFE for its low thermal conductivity, which prevents bristles from sticking to hot surfaces during treatment, whereas the patent ‘Sunscreen compositions containing fluorinated alkyl ethers’ (US8206728 B2) described the use of fluorinated alkyl ethers for their unexpected increase in SPF value. However, similar to other patents, PFAS were also described in cosmetics and personal care products for their lipophilicity and oil and water repellence.

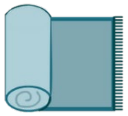
Electronics. The CPC class capturing phones, televisions, and speakers was largely comprised of patents related to pictorial communication (e.g., television) (29%). Additional patents included loudspeakers, microphones, etc. (26%); transmission of digital information or telegraphic communication (17%); and transmission (11%). Patents related to televisions included housings for electronic devices (US10945061 B2), information display protectors (WO2021141579 A1), projection television receiver (US20220201387 A1), and others. Among those patents, fluoropolymers and fluorochemical mixtures were used for an anti-smudge coating, abrasion and stain resistance, and sealant. Additional uses for fluoropolymers presented by patents related to speakers and telephones included antifouling, insulation, and oil and water repellence.



Food Products. The patents for food products were all contained within the subclass for food, foodstuffs, and non-alcoholic beverages (A23L). Within this CPC code, three groups comprised almost three-fourths of the patents: modifying nutritive qualities of foods, dietetic products (30%); preparation or treatment and preservation of foods/foodstuffs (30%); and non-alcoholic beverages, including concentrates (17%). Additional groups contributing to the patents included preservation of foods or foodstuffs (9%) and the preparation or treatment of spices, condiments, artificial sweetening agents, or salt substitutes (4%).

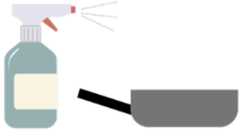
- **Food Products.** PFAS are not intentionally added to food, but the search did capture elemental fluorine which may be added as a nutrient supplement.
- **Furniture, Furnishing and Décor.** PFAS are common in patents for carpet, furniture fabric, mattresses, and even sleeping bags because of its insulating ability and its known water- and stain-repellent properties, as well as its lubrication and friction durability.

A review of the subclass indicated that while elemental fluorine may be intentionally added as a nutrient in food, PFAS did not appear to be intentionally added to food products as a nutrient supplement or otherwise. Some patents mentioned the use of a kitchen appliance coated with PFAS to provide nonstick functionality. For example, fluorine is mentioned for use in coating the pot and stirring rod for the preparation of a buckwheat dough stick (JP2001045997 A), and a fluororesin is suggested for coating the surface of a molded sheet to create sushi rolls (JP4217690 B2).



Furniture, Furnishing and Décor. Within the “Furniture, Furnishings, and Décor” category, patents for fabric treatments and upholstery, plus coatings for flooring finishes are common. In the fabric treatment section, patents for floor fabrics and fastenings demonstrated that fluororesins are used to prevent antifouling against dry and wet soil in carpets (US20220010486 A1). Fabrics are also treated with fluorochemicals as a water and alcohol repellent (US20210363690 A1; US20210289899 A1). Some additional patent examples also mention the use of fluorinated polymers for lubrication (US10302130 B2) and friction durability (US11504740 B2). The upholstery category provides additional insight on PFAS use for thermal regulation with insulation fabric; a water-repellent coating in multi-functional upholstery in mattresses, chairs, beds or sofas (KR100566043 B1); and antibacterial properties and water-proofing for sleeping bags (CN114224143 B).

In addition to the common functionality of anti-wear, anti-fouling, and wear resistance (US20180230324 A1), fluorine polymers and additives are also used in floor coating formulations to aid in flow, wetting, and leveling (US6660828 B2).

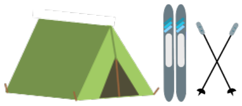


Household Products and Small and Large Appliances. Among CPC code A47, most patents (54%) related to kitchen equipment, mainly cooking vessels; parts, details, or accessories of cooking vessels; and baking, frying, grilling, and roasting apparatuses or equipment. Patents under cookware included containers for cooking, cookware sets, filters for espresso machines, utensils for cooking, and others. Among those examples, fluoropolymers, including PTFE and tetrafluoroethylene (TFE), were most often cited for their use in creating an anti-adhesion/nonstick layer. Additional uses of PFAS in cookware included corrosion resistance and thermo-stability. Notably, while nonstick layers were often associated with preventing food from sticking to cookware, the patent for cooking utensils (US20080061068 A1) specifically cited the use of the fluoropolymer layer to avoid growth of bacteria.

- **Household Products.** Patents for PFAS in kitchen equipment often relate to its nonstick and anti-adhesion properties, corrosion resistance, thermostability, and occasionally antibacterial properties.
- **Outdoors, Outdoor Recreation, Sports, and Fitness.** PFAS in ski wax and shoes are well-known for their lubrication, thermal regulation, and water repellent properties. They are also used in camping equipment and playgrounds for like reasons plus corrosion resistance.

In addition to cookware, patents related to household products also captured dry-cleaning, washing, or bleaching and cleaning products, and detergents. Fluorosurfactants in cleaning product compositions were used to reduce surface tension and low-foaming behavior. Additional fluorinated compounds and fluoropolymers were used for oil and water repellence and stain resistance. Also of note was the patent entitled ‘Scrubbing-free car washing powder’ (CN111304018 A) which cited the use of perfluoropolyether and fluorosilicone resin to repel dust, fog, and water.

Note that due to the structure of the CPC codes, patents related to household products and small and large appliances were not mutually exclusive as shown in **Table 4-1**. For example, the CPC code A47 includes furniture, domestic articles, and appliances.



Outdoors, Outdoor Recreation, Sports, and Fitness. Within the CPC class for amusements, games, and sports, many patents pertain to apparatuses for physical training and training equipment (51%), and board, card, roulette games and video games (33%). Example patents for physical training and training equipment include compositions for ski wax, skiing sole coatings for ski shoes, golf balls, and others. Among patents pertaining to ski wax and skiing sole coatings for ski shoes, fluoropolymers and fluororesins were used as lubricating agents and for water repellence. The patent for a golf ball (US11511162 B2) cited the use of a fluorocarbon polymer (such as PTFE) to reduce surface energy.

Also, of note for outdoor recreation are patents for camping equipment (i.e., shoe lacing fastenings and traveling containers) and pavings or foundations for playgrounds or sports grounds. Like that previously described, the camping equipment utilized fluoropolymers and fluorinated resins for water repellence. Thermal regulation to allow for evaporation was also cited for the patent on self-cooling containers for liquids (US7107783 B2). The pavings or foundations also utilized the water repellence and corrosion resistance of fluorinated substances.

Toys, Hobbies, and Crafts. Unlike the other consumer product categories, only one CPC code was used to search for the "Toys, Hobbies, and Crafts" category—A63: Sports; Games; Amusements, which includes building blocks, dolls, hoops, tops, and others. Patents among the toys were related to building blocks and plush toys. Two examples in particular cited use of PFAS for reasons that were unique relative to the examples described in the previous consumer product categories. For an antibacterial plush toy fabric (CN202410140 U), fluoroplastics (i.e., PTFE) are used to refine the plush materials and reduce bacteria and dust accumulation, whereas for building blocks (JP3194199 U), a fluororubber is used to soften the material to prevent injuries for its users. The use of PFAS for its abilities to reduce bacteria and soften material are particularly significant for use in children's consumer products.

4.1.2 PFAS in Current or Prior Commercial Use

General Consumer Products from Datasets and Literature

Potential functional uses of PFAS in consumer products were provided by the patents. However, literature has reported detected PFAS in consumer products under and adjacent to CPSC jurisdiction including: cleaning products; cosmetics and personal care; electronics; medical uses; packaging, paper, and cardboard; plastics; textiles; and others (Gaines, 2023; Glüge et al., 2020). One overview of PFAS uses in consumer products and industry sectors reports extensive use of PFAS with more than 200 use categories and subcategories and more than 1,400 individual PFAS (Glüge et al., 2020). As referenced in the patents, PFAS have several functional uses with one of the most common uses as a dirt, grease, and water repellent making PFAS ideal for use in food packaging and outdoor clothing. Other common functional uses include adhesives and sealants, lowering the surface tension of paints to result in easier flow and glossy finishes, lubrication and nonstick properties for cookware, and others (ChemSec, 2023).

According to the database we compiled, 863 individual PFAS were identified as present in consumer products as indicated by analytical detection or current or historical reports. In contrast with (Gaines, 2023) and (Glüge et al., 2020), the 863 PFAS identified excludes PFAS with explicit use reported in industrial products. For instance, (Glüge et al., 2020) reported on PFAS used in aerospace and energy sections, which were excluded from the consumer products database (see additional details on exclusions in **Appendix A**).

The 863 PFAS known to be present in consumer products were categorized according to the classifications in **Figure 2-2** and shown in **Table 4-2**. Many of the consumer product chemicals were non-polymers (n = 690, 80.0%), which was expected given the limits in characterizing polymeric PFAS with current methods (see **Section 2.1.4**). Among the non-polymers that were further classified, fluorotelomer substances was one of the largest categories (n = 145, 16.8%). Many of the non-polymeric PFAS were only categorized at the subclass level due to chemicals being a PFAA precursor or having undefined structures.

Table 4-2. PFAS Reported in Consumer Products

		Consumer Products	
Classification	Category	*n*	(%)
	Non-Polymers		
Subclass	Perfluoroalkyl Substances	306	35.5
Group	PFAAs	106	(12.3)
Group	FASAs	16	(1.9)
Group	Perfluoroalkyl Ether Acids (PFEAs)	11	(1.3)
Group	Perfluoroalkane Sulfonyl Fluorides	6	(0.7)
Group	Perfluoroalkyl Iodides	3	(0.3)
Group	Perfluoroalkanoyl Fluoride	1	(0.1)
——	Not Further Classified	164	(19.0)
Subclass	Perfluoroalkyl Substances	384	(44.5)
Group	Fluorotelomer Substances	145	(16.8)
Group	Perfluoroalkane Sulfonamido Substances	68	(7.9)
——	Not Further Classified	171	(19.8)
	Polymers		
Subclass	Side-Chain Fluorinated Polymers	108	(12.5)
Subclass	Fluoropolymers	57	(6.6)
Subclass	PFPE	2	(0.2)
Undetermined		6	(0.7)
Total		863	(100.0)

Polymers were primarily comprised of side-chain fluorinated polymers (n = 108, 12.5%). Additionally, six chemicals were classified as undetermined because the chemical name was not sufficient for categorization, and the structure was undefined. Some chemical names in the master list are generic due to CBI. More details on these PFAS can be found in the database (*PFAS Source Characterization Database.xlsx*).

To supplement the database, studies from the literature review on PFAS exposure (see **Sections 3.4** and **4.4.2**) were leveraged to identify additional information on the presence of PFAS in consumer products. A total of 400 studies were tagged as containing any information on consumer products. Studies included quantification of PFAS in consumer products with some studies also estimating exposures for population groups by quantifying dose and intake.

Table 4-3 summarizes information on consumer products obtained from literature. Note, these studies have not been extracted for specific PFAS or extracted for inclusion in the database. The PFAS reported in these studies were limited to those that can be measured using existing methods (see additional information in **Section 2.1.4**). Based on cursory screening, these studies appear to report on a limited number of PFAS that were already identified as present in consumer products from database, rather than providing new information on novel PFAS.

Future steps could include chemical-specific extraction of information from these studies. More details on these studies can be found in the database (*PFAS Literature on Exposure, Toxicity, and Health Risk.xlsx).*

Table 4-3. Count of Studies Containing Information on Consumer Products.

Product Category	Counts
High Priority Consumer Products, or Products Adjacent to CPSC Jurisdiction	
Childcare Products	2
Clothing, Apparel, Jewelry, and Accessories	12
Containers and Packaging	30
Cosmetics and Personal Care Products	14
Electronics	0
Food Products	325
Furniture, Furnishings, and Décor	24
Household Products	16
Infant Formula	7
Outdoors, Outdoor Recreation, Sports, and Fitness	7
Small and Large Appliances	1
Toys, Hobbies, and Crafts	0
Non-Consumer Products or Materials	
Industrial Product or Material	17
Manufacturing Product or Material	4
Recycled Product or Waste	8
Supplemental Products and Materials	
Controlled Items	9
Medical Products	1
Miscellaneous Household or Industrial Products	12

These studies along with reports from several authoritative agencies, environmental health organizations, and researchers are summarized in the following sections. However, given the number of PFAS-containing consumer products, the following sections are not exhaustive, but instead provide an overview of products with some examples shown in **Table 4-4.** Subsequently, PFAS-containing products classified as toys, hobbies, and crafts; electronics; or small or large appliances are not characterized. However, the previous section on patents detailed the function and use of PFAS in those applications. For example, PFAS were reported across the electronic and semiconductor industry with PFAS used in mobile devices for anti-smudge on the touch panel and smoothness and dielectric properties, electric insulation, and molding and processing for electric cables and wires (Tansel, 2022).

Table 4-4. Example General Consumer Products with Detected PFAS.

Consumer Products		Reference(s)
Clothing, Apparel, Jewelry, Accessories; Furnishings, Furniture, and Décor		
Backpacks Black Shoe Leather Carpets Floor and Wall Coverings Gloves Jackets Laminated Plastic Floor Covering	Office Furniture Leather Office Furniture Textile Outdoor Clothes Outdoor Pants/Trousers Outdoor Shirts/Pullovers Outdoor Textiles Resilient Linoleum Tablecloth	(Greenpeace, 2016; Wu et al., 2020; Herzke et al., 2012; Gremmel et al., 2016; van der Veen et al., 2020; Schreder & Goldberg 2022; Kotthoff et al., 2015; Gaines, 2023; Glüge et al., 2020)
Containers, Packaging		
Fast Food Paper Boxes Fast Food Wrappers Ice Cream Cups	Microwavable Popcorn Bags Paper-Based Food Contact Materials	(Zafeiraki et al., 2014; Kotthoff et al., 2015; Glüge et al., 2020; Gaines, 2023)
Cosmetics, Personal Care Products		
Bar Soap Body Lotion, Creams, and Oils Cosmetic Makeup (e.g., Concealer, Foundation, Mascara)	Dental Floss Menstrual Underwear Sunscreen	(Rodgers et al., 2022; (Segedie, 2021; Whitehead et al., 2021; Gaines, 2023; Glüge et al., 2020)
Household Products		
Baking Ware Cleaning Agents Cleaning Compositions in General	Nonstick Cookware Pans Toilet Paper	(Kotthoff et al., 2015; Thompson et al., 2023; Herzke et al., 2012)
Outdoors, Outdoor Recreation, Sports, Fitness		
Artificial Turf Rope Sleeping Bags	Tents Ski Wax	(Greenpeace, 2016; Fang, 2020; Carlson & Tupper, 2020; Kotthoff et al., 2015)

Textiles

Clothing, Apparel, Jewelry, and Accessories. For textiles, particularly clothing, PFAS are incorporated for their ability to repel dirt, oil, and water (Glüge et al., 2020; Gaines, 2023). Clothing labeled as durable water resistant (DWR) are often treated with polymers including fluoropolymers or side-chain fluorinated polymers. Clothing, and other textiles such as bed linens, carpets, tablecloths, and upholstery, are also often treated with fluorotelomer substances, including FTOHs, and other PFAS (Friends of the

Earth Norway, 2006; Herzke et al., 2012; Kotthoff et al., 2015). Side-chain fluorinated polymers and FTOHs are described to have major uses for surfactants and in surface protection products (Buck et al., 2011).

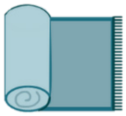
Several studies have targeted outdoor gear where durability and water resistance are desirable (Gremmel et al., 2016; van der Veen et al., 2020). In an analysis of 24 PFAS, represented by several groups—PFAAs, FASAs, perfluorooctane sulfonamidoethanols, and FTOHs—all 16 jackets tested had detectable levels of PFAS with varying ranges (Gremmel et al., 2016). PFOA was detected in all jackets, but the highest concentrations were among the FTOHs (Gremmel et al., 2016). Results were in line with a subsequent study on outdoor clothing samples, including outdoor clothes, jackets, and trousers (van der Veen et al., 2020). While dermal absorption of PFAS has not been well-characterized, authors underscore how the use of outdoor clothing may be a potential exposure route for humans, particularly throughout wear and tear of the clothing (see **Sections 4.1.2** and **4.4.2**)

APPLICATION #1

- General Product
    - Consider the purchase of a new adult rain jacket labeled as DWR. The designation as water-resistant may be an indicator that the jacket was treated with PFAS, such as fluorinated side-chain polymers or FTOHs.
    - Even if the jacket is labeled as “PFAS-free,” PFOA-free,” or “PFOS-free,” it is possible the jacket was treated with lesser known PFAS or contaminated with PFAS in the manufacturing process.
- Children’s Product
    - Consider the purchase of a new child feeding bib labeled as stain-resistant. Like the adult rain jacket, the child feeding bib is likely to be treated with PFAS to impart stain resistance.

Additionally, in 2015, Greenpeace, an independent global campaigning network, reported on PFAS measured in outdoor products, including backpacks, gloves, jackets, shoes, and trousers among popular outdoor/recreation brands (Greenpeace, 2016). (Additional items reported on are described in the “Outdoors, Outdoor Recreation, Sports, Fitness” category.) Seven of the eight backpacks, nine of the 11 jackets, and all but one sample of gloves had detectable levels of the PFAS measured. Compositions and concentrations of PFAS varied greatly across products, but volatile PFAS (FTOHs and fluorotelomer acrylates) dominated samples by concentration for both jackets and trousers.

Other environmental health advocacy and campaigning groups and networks have also tested outdoor apparel. In an analysis of outdoor apparel, including jackets, pants, and shirts/pullovers, 15 of the 20 items had detectable levels of PFAS tested. Notably, all products tested were labeled as water- or stain-resistant, and in agreement with the other studies mentioned in this section, FTOHs, especially 6:2 FTOH, were prevalent (Schreder & Goldberg, 2022).



Furnishings, Furniture, and Décor. Carpeted floors, commercial carpet-care liquids, and pre-treated carpet may be the most significant sources of perfluorocarboxylic acids (e.g., perfluoropentanoic acid [PFPeA], perfluorohexanoic acid [PFHxA], PFHpA, PFOA, perfluorononanoic acid [PFNA], PFDA, PFUnA, and perfluorododecanoic acid [PFDoA]) relative to 10 other article categories in the typical United States home (Guo et al., 2009). Notably, in a follow-up study focused on the determination of FTOHs, 6:2 FTOH and 10:2 FTOH were not detected in household carpet/fabric-care liquid and foam samples and only one of five carpet samples (Liu et al., 2015).

Carpets and rugs are known to contain PFAS whether due to intentional additions for water- and stain repellence and/or use of recycled materials. PFAS may also be added to carpets during use through carpet cleaning (Wu et al., 2020). In a study that analyzed carpet fibers and materials from Californian childcare centers, 40 out of 42 targeted PFAS were detected with eight PFAS detected in all samples (PFBS, PFOS, 6:2 FTOH, 8:2 FTOH, PFPeA, PFOA, and PFNA) (Wu et al., 2020). PFAS levels in the carpet samples were associated with the levels in the dust samples also analyzed. Carpets can be an important source of exposure for small children, especially those with frequent hand-to-mouth behaviors.

In addition to carpets, rugs, and related treatments, datasets included reported PFAS in bedding products, foam seating, leather, linoleum, and wood furniture. One report by the HPCDS included a blanket or throw with detectable PFOS. However, it was considered a contaminant rather than intentionally added for a functional or technical purpose.

Containers and Packaging. Food contact materials (FCMs) or food contact substances are packaging materials used for consumer items and food. Common FCMs include food wrappers, microwavable popcorn bags, and pizza boxes. PFAS are often used in FCMs due to their grease- and water-repellent properties and thermal stability and incorporated either internally or externally as a surface treatment (Dutch National Institute for Public Health and the Environment, 2018). PFAS are incorporated for such properties regardless of packaging type—bioplastic, plastic, pulp fibers (Semple et al., 2022). PFAS can also be used in the coatings for FCMs to impart durability as reported by ChemSec. Data from the Food Contact Chemicals Database reported the presence of 158 unique PFAS in FCMs for adhesives, coatings, plastics, rubber, and others. However, among all reports categorized as "Containers and Packaging," which also includes non-food related packaging (e.g., paper and cardboard), 311 unique PFAS are represented across datasets. The "Containers and Packaging" category has the second largest number of unique PFAS reported in the database—second to the "Industrial Product or Material" category with 356 unique PFAS reported (see *PFAS Source Characterization Database.xlsx* for additional details). The primary concern with PFAS in these products is the potential for the chemicals to migrate into food as described in further detail in **Section 4.4.2**.

Fast Food Packaging. Several different FCMs and packaging have been reported with detectable PFAS (Schaider et al., 2017; Kotthoff et al., 2015; Zafeiraki et al., 2014; Liu et al., 2015). Total fluorine and certain PFAS (e.g., perfluorocarboxylic acids, perfluorosulfonic acids (PFSA), and fluorotelomer sulfonates) have been detected in packaging from United States fast food restaurants, including bread and dessert wrappers, burger and sandwich wrappers, and paperboard (Schaider et al., 2017). Additionally, ice cream cups, fast food paper boxes from Greek markets and retail were analyzed for 12 PFAS and resulted in detections, while beverage cups, paper materials for baking, or aluminum foil bags/wrappers had no detected PFAS (Zafeiraki et al., 2014). Large variability was reported for total FTOHs (sum of 6:2, 8:2, and 10:2 FTOH) detected in nine treated food contact papers (Liu et al., 2015).

Microwavable Popcorn Bags. Based on data between 2005 and 2018, PFOA and PFOS concentrations are declining in microwavable popcorn bags. Among the seven popcorn bags analyzed in a 2018 study, only two samples had detectable levels of PFOA, and no samples had detectable levels of PFOS (Monge Brenes et al., 2019). Additionally, the three samples of snack and sandwich bags tested had no detectable levels of PFOA or PFOS (Monge Brenes et al., 2019). These results were consistent with another study that analyzed 12 PFAS in three microwave popcorn bags collected in 2012 (Zafeiraki et al., 2014). PFOA and PFOS were not detected before or after cooking; however, concentrations of perfluorobutanoic acid (PFBA), PFPeA, PFHxA, and perfluoroheptanoic acid (PFHpA) varied before and after cooking, ranging from below the level of detection to 681.35 ng/g (maximum reported for PFHxA) (Zafeiraki et al., 2014).

Although, studies of (Zabaleta et al., 2017; Zabaleta et al., 2016) have underscored differences in PFAS contributions, including PFOA, based on country of origin.

Cosmetics and Personal Care Products. Several cosmetics and personal care products were reported in the Chemical and Products Database (2020), including anti-aging cream, antiperspirants, body creams and lotions, shampoo, soaps, sunscreens, and others (see *PFAS Source Characterization Database.xlsx* for additional details). Given the frequency of use of cosmetics and personal care products, PFAS exposure and risk from those products are of particular concern.

Feminine Hygiene Products. Recently, concern has been raised over PFAS content in different feminine hygiene products, especially menstrual underwear. In 2020 tests of consumer products, including six samples of menstrual underwear for analysis, one sample had a total fluorine concentration of 1,456 parts per million and detectable PFAS (Rodgers et al., 2022). Other analyses of menstrual underwear resulted in two brands undergoing class-action lawsuits because one brand labeled the product as “PFAS-free,” while the other labeled the product as “organic, sustainable, and nontoxic” even though both were found to contain PFAS. The latter brand claimed that PFAS were never included in the product design, which raises questions of PFAS byproducts or contamination throughout the manufacturing process (described in further detail in Section 4.1.2). As a result of the lawsuit, the company stated that it would take additional steps to ensure PFAS are not intentionally added to its products at any stage of product manufacturing, including when receiving raw materials from suppliers (Treisman, 2023; Persellin, 2022).

Cosmetics. Total PFAS concentrations have varied considerably across cosmetic products. The Danish EPA analyzed the presence and risk of PFAS in 20 cosmetic products, including two control products that had no declared content of PFAS on the ingredient list (Danish EPA, 2018). Products included blemish balms, body lotions, color correcting creams, concealer, cream/lotion, eyeliner, eye shadow, facial scrubs, foundation, hair spray, highlighter, and powder. The control products were body lotion and foundation. Among the 22 PFAS analyzed, five were not detected in any of the products (perfluorohexanesulfonic acid [PFHxS], perfluoroheptane sulfonic acid [PFHpS], PFOS, perfluorooctanesulfonamide [PFOSA], and perfluorodecane sulfonic acid). Apart from those with all non-detects, total PFAS concentrations varied from 0.69 ng/g to 10,700 ng/g. The minimum corresponded to hairspray that declared polyperfluoroethoxymethoxy difluoroethyl peg phosphate on the International Nomenclature of Cosmetic Ingredients list, whereas the maximum corresponded to concealer that declared $C_{9\text{-}15}$ fluoroalcohol phosphate. Authors noted that regardless of the declared ingredients, potential PFAS degradation products may be formed throughout use that are not declared on the list.

Similarly, cosmetic products specifically purchased from retailers in Canada and the United States also exposed gaps in labeling laws; much of the ingredient lists did not disclose fluorinated compounds or PFAS. However, high fluorine concentrations were found in products commonly advertised as “long-lasting” or “wear-resistant” to oils and water, including waterproof mascaras (Whitehead et al., 2021). Additional gaps in PFAS labeling are in **Section 4.1.2.**

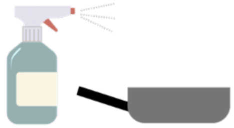
Food Products. Except for drinking water, food products are among the most well-studied media with respect to PFAS levels, especially seafood products. In 2019, FDA began testing foods from the general food supply and from specific areas potentially affected by environmental contamination. The analytical methods used are only validated for 16 different PFAS as of 2019 and 20 as of

2022 (U.S. Food & Drug Administration, 2022b). For the Total Diet Study samples, multiple collections of food samples were tested, but sample sizes were limited. The overall results of the five datasets published for the Total Diet Study are shown in **Table 4-5**.

Table 4-5. Overview of Results from the U.S. FDA Total Diet Study for PFAS

Dataset	Samples with Detectable Level(s)	Total Samples	Details [a]
1 [b]	2	91	PFOS detected in ground turkey (85.7 ppt) and raw tilapia (87 ppt)
2 [c]	1	88	PFOS detected in raw tilapia (83 ppt)
3 [d]	1	94	PFOS detected in baked cod (98 ppt)
4 [e]	3	167	PFOS and PFNA detected in frozen oven-cooked fish sticks or patty (33 ppt and 50 ppt, respectively) PFOS and PFDA in drained, canned in water tuna (76 ppt and 72 ppt, respectively) PFOS in protein powder (140 ppt)
5 [f]	3	94	PFOS in baked tilapia (28 ppt) PFOS, perfluoroundecanoic acid (PFUnA), and PFDoA in pre-cooked shrimp with shells removed and no tails (216 ppt, 233 ppt, and 71 ppt, respectively) PFDA, PFNA, and PFUdA in baked cod (23 ppt, 87 ppt, and 151 ppt, respectively)

[a] All concentrations reported are in parts per trillion (ppt).
[b] FDA (2019a)
[c] FDA (2019b)
[d] FDA (2021a)
[e] FDA (2021b)
[f] FDA (2022)



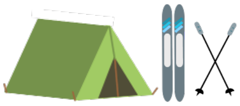
Household Products. Several functional uses of PFAS, including chemical stability, high acid resistance, and lower surface tension, are imparted to household products such as carpet spot cleaners, cookware, dishwashing liquids, floor polish, and others (Glüge et al., 2020).

The use of PFAS in cookware is most notable for imparting nonstick properties. Polymeric PFAS are commonly reported in nonstick cookware with the most common fluoropolymers being PTFE, fluorinated ethylene propylene (FEP), and perfluoro-3-[(trifluoroethenyl)oxy]propane, polymer with tetrafluoroethene (CASRN 26655-00-5) according to one review (Glüge et al., 2020).

As of March 2023, a peer-reviewed journal article reported occurrence of select PFAS in toilet paper (Thompson et al., 2023). Toilet paper samples were collected from Chile, Costa Rica, El Salvador, France, Netherlands, South Africa, United Kingdom, United States, and Uruguay. Of the 34 PFAS analyzed, at least one of six compounds (PFHxA, PFOA, PFDA, 6:2 fluorotelomer phosphate diester, 6:2/8:2 fluorotelomer phosphate diester, and 8:2 fluorotelomer phosphate diester) were detected in each of the 21 samples. The authors discussed the contribution toilet paper could have on PFAS in wastewater with subsequent environmental and human exposures via wastewater effluent and sludge used for irrigation and/or land application. However, the authors did not address direct dermal exposure to PFAS from use of toilet paper. These exposure pathways and sources are further described in **Section 4.4.2**.

In addition to toilet paper, other household products analyzed include cleaning agents. In one study, nine samples of cleaning agents were analyzed for PFAAs (perfluoroalkyl carboxylic and sulfonic acids) and FTOHs (Kotthoff et al., 2015). The PFAA concentrations were considered negligible (<0.5 parts per billion, ppb) except for PFOS in one sample (1.1 ppb), while FTOH concentrations were considerably higher (≥ 100 ppb). Three compounds were detected in all samples (6:2 FTOH, 8:2 FTOH, and 10:2 FTOH) ranging up to 547,100 ppb.

One report noted how the percentage of PFAS in cleaners are variable (Gaines, 2023). While some cleaners only report a small percentage of PFAS, some 3M contact cleaners contain two PFAS that make up 95%–99% of the cleaner's weight (Gaines, 2023). Across datasets, different cleaning products (e.g., cleaning compositions for dishes and glasses, cleaning compositions for metal surfaces) dominated (90%) the "Household Products" category. The other reports were comprised of baking ware and cooking ware with PFAS used to impart nonstick properties—frying pans and other nonstick utensils, tools, and cutlery.



Outdoors, Outdoor Recreation, Sports, Fitness. Among outdoor recreation and sports products, ski waxes are among the most well-known for containing PFAS. The majority (59%) of reports across datasets pertained to ski wax (see *PFAS Source Characterization Database.xlsx* for additional details). The peer-reviewed literature has investigated ski wax and the potential health hazards among ski wax technicians and recreational skiers applying those waxes. In 2020, the European Union banned PFOA (and substances that might form PFAS in the environment) in all products sold in the European Union (EU), which included ski waxes. Additionally, the International Ski Federation also banned fluorocarbon-based waxes in competitions with intentions to start in the 2020–2021 winter season (Fang et al., 2020; International Ski and Snowboard Federation, 2022). Considering those regulations, the best-selling ski wax products in Norway were assessed in the summer of 2019, and all 11 commercial ski wax products had detectable levels of perfluoroalkyl carboxylic acids (PFCAs) and varying levels of other PFAS (Fang et al., 2020). The results indicated that there was no change in ski wax formulations; however, ski wax manufacturers have reported research and development of fluorinated-free ski waxes (Fang et al., 2020). The authors suggested that rather than changing ski wax formulations, manufacturers continue to produce fluorinated ski waxes alongside the fluorinated-free ski waxes.

In addition to the ban by the International Ski Federation, there have been other bans for some types and uses of fluorinated ski waxes by other skiing associations, Nordiq Canada, and several states in the United States. One of those states includes Maine; however, a study conducted in 2020 also revealed high levels of both long- and short-chain PFAS in the snow at race starts (Carlson & Tupper, 2020).

Artificial turf is another outdoor recreation product that has been subject to regulation (see **Section 4.3.1**). Peer-reviewed literature on the presence of PFAS in artificial turf is limited; however, PFAS could be used in the plastic and rubber production as a processing aid (Glüge et al., 2020). PFAS may also impart certain functional uses, including enhanced smoothness and reduced friction, to the turf (Stade, 2019). In a press release, the Public Employees for Environmental Responsibility (PEER) and The Ecology Center reported the presence of 6:2 fluorotelomersulfonic acid (6:2 FTSA) in the backing of new turf used at a high school in Massachusetts. Other turf samples had detectable levels of PFOS or total fluorine levels indicative of PFAS presence (Stade, 2019).

Furthermore, PFAS are cited in other consumer products for outdoor recreation and sports. Datasets reported on bicycle lubricant, coating for tennis rackets, fishing lines, and textiles for sailing boat equipment (see *PFAS Source Characterization Database.xlsx* for additional details).

In the report previously described by Greenpeace, rope, sleeping bags, and tents were also measured for PFAS. Each of the five sample products had detectable levels of at least one of the PFAS measured. Concentrations varied, but for the one rope, two sleeping bags, and one tent, 6:2/8:2 FTOH dominated. The other tent sample only had low concentrations of PFOA.

Children's Products from Datasets and Literature

Children's products are those designed or intended primarily for children 12 years of age or younger. In determining whether products are general consumer products or children's products, CPSC has Age Determination Guidelines. CPSC has stated that the guidelines are important for ensuring that products are safe and developmentally appropriate for the targeted audience (CPSC, n.d.).

> While the literature appears to be limited for children's products, PFAS have been detected in children's bedding, bibs, car seats, clothing, and nap mats.

The presence of PFAS in children's products can pose a particular challenge with respect to ensuring that products are safe; however, data and peer-reviewed literature analyzing childcare products are limited. For instance, the HPCDS includes reporting from Oregon and Washington regarding high priority chemicals of concern to children's health. The reporting is restricted to PFOS and its salts for Oregon and PFOA, PFOS, and their salts for Washington. Other PFAS have yet to be added to the list of high priority chemicals of concern to children's health. Reports were primarily for apparel, including baby feeding bibs, bodysuits, dresses, jackets, shirts, skirts, and others. The other product category represented was for "Toys, Hobbies, Crafts" including artists accessories and board games/cards/puzzles variety pack. Notably, in both product categories, there were reports that indicated PFOS had no chemical function but instead was a contaminant in the inks/dyes/pigments, synthetic polymers, surface coatings, or textiles. In addition to HPCDS, later iterations of U.S. EPA's CDR database specified whether products were for children's use. Reports were still limited in details and volume but included general arts, crafts, and hobby materials; fabrics, textiles, or leather products; foam seating and bedding products; and toys, playground, and sporting equipment (see *PFAS Source Characterization Database.xlsx* for additional details).

Textiles. In the High Priority Chemical Database, PFOS was reported in apparel such as jackets, pants, and sportswear as a surface coating to impart waterproofing. Jackets, especially those labeled as "all-weather," are often treated with PFAS (Friends of the Earth Norway, 2006). In one investigation of all-weather jackets for children across five different brands, FTOHs and PFCAs were detected in all samples (Friends of the Earth Norway, 2006). For most samples, 8:2 FTOH and 10:2 FTOH were the largest contributors to total PFAS (Friends of the Earth Norway, 2006).

The nonprofit, nonpartisan activist group, Environmental Working Group, analyzed several childcare products first for total fluorine and then a subset of products for 70 different PFAS (Evans & Persellin, 2022). Authors underscored that total fluorine concentrations are a proxy for both polymeric and non-polymeric PFAS. Children's bedding, bibs, clothing, and a snack bag had the highest total fluorine concentrations, while a bib labeled as waterproof had the highest sum concentration of PFAS (191.985 ng/g). In another study, authors analyzed three children's product categories: school uniforms, weather-resistant outdoor wear (i.e., mittens, rainsuits, snowsuits, and snowshoes), and miscellaneous (i.e., baby shoes, bibs, hats, stroller covers, sweatshirts, and swim wear) (Xia et al., 2022). Products were selected based on certain labels:

waterproof/water-resistant/durable water-repellent, stain-proof/stain-resistant/easy care stain release, windproof, or wrinkle resistant. School uniforms and weather-resistant outdoor wear had similar sum concentrations of 49 PFAS—median of 728 ng/g and 111 ng/g, respectively. Sum concentrations were dominated by FTOHs and fluorotelomer methacrylates.

Car Seats. The Danish EPA analyzed 22 products treated with PFAS-containing impregnating agents and eight car seats obtained from a separate study (Danish EPA, 2015). Products included children's car seats, gloves, infant sleeping bags, jackets, rain suits, and snowsuits. Total fluorine analyses were first conducted to determine which products would be further analyzed for PFAS; 19 of the 22 items of children's clothing and infant sleeping bags had detectable levels of fluorine, while none of the car seats had detectable levels. Danish EPA selected 15 items to be carried through for analysis of 37 target PFAS, wherein the total PFAS concentrations ranged between 14.60 and 422.35 μg/m^2. The three products (infant sleeping bag, mittens, and rainsuit) made with a particular PTFE component contained high concentrations of total PFAS (125.09 to 422.35 μg/m^2) with 8:2 FTOH accounting for greater than 65% of the total. For all products, FTOHs accounted for 46% to 99% of the total content of PFAS. Additionally, perfluoroalkyl carboxylates were also among the products with PFOA being the predominant substance. Concentrations of PFOS, other perfluoroalkane sulfonic acids, and other PFAS categories were relatively low.

Conversely, a study that analyzed 18 children's car seats manufactured in 2017 and 2018 (produced in China, Canada, and the United States) detected at least one PFAS in 97% of the samples—composite (n = 16), fabric (n = 15), and foam samples (n = 5) (Wu et al., 2021). Median concentrations for the sum of 42 PFAS concentrations were 12.3 ng/g, 47.3, and 12.1 ng/g for composite, fabric, and foam samples, respectively. 6:2 FTOH had the highest detection frequency among composite and fabric samples (56% and 57%, respectively), as well as the highest median concentrations (3.08 ng/g and 3.54 ng/g, respectively) (Wu et al., 2021). Furthermore, based on particle-induced gamma-ray emission spectroscopy (measures total fluorine as noted in **Section 2.1.4**), authors suggested the presence of fluorinated polymers (Wu et al., 2021).

Nap Mats. PFAS have also been reported in children's nap mats collected in seven Seattle childcare facilities (Zheng et al., 2020). Twenty-one of the 37 PFAS analyzed (including both perfluoroalkyl substances and polyfluoroalkyl substances—PFAAs; FASAs; perfluorooctane sulfonamidoethanols; and fluorotelomer, sulfonates, alcohols, and acrylates, and fluorotelomer methacrylates) were detected among 26 mat samples—both new and used. The sum of 21 PFAS concentrations ranged between 1.6 and 600 ng/g (Zheng et al., 2020).

4.1.3 PFAS Lifecycle

PFAS are synthetic compounds, therefore, the lifecycle (illustrated in **Figure 4-4**) begins with the production of chemical feedstock used to manufacture PFAS. Once PFAS are produced or synthesized, there are several reported industries that use PFAS. PFAS may be used to aid in the manufacturing process and used in the production of consumer and industrial products. From there, the PFAS-containing products are distributed into commerce, used, and disposed.

Figure 4-4. Lifecycle of PFAS

At any of the stages of the lifecycle, PFAS can be released and further accumulate into the environment, which can result in ecological and human exposure. The following are potential release points for PFAS at each stage of the lifecycle:

- **Feedstock Chemical Production:** Direct PFAS release is not likely but is a potential source of other releases, including PFAS precursors.
- **PFAS Production**: Direct PFAS release may occur through air emissions or industrial discharges to surface waters.
- **Product Manufacturing**: Similar to PFAS production, as manufacturers incorporate PFAS into consumer products, direct PFAS release may occur.
- **Product Use:** Direct PFAS release may occur through air emissions during use (e.g., for cookware), direct contact, or mouthing PFAS-containing objects, resulting in PFAS in the indoor and outdoor environments. While many consumer products contain PFAS, mediated and contact exposures in the indoor environment are not well-characterized. There is limited evidence that PFAS used in consumer products can be released to the indoor environment through abrasion, direct transfer, or mass transfer. Additional information on exposure scenarios is in **Section 4.4.2**.
- **End-of-Life Management:** All products manufactured with PFAS ultimately end up in the waste stream and managed via various end pathways (e.g., combustion, composting, landfills, recycling, septic tanks, and surface water discharge after wastewater treatment).

The following section primarily focuses on the latter four stages of the lifecycle: PFAS production, product manufacturing, product use, and end-of-life management.

PFAS Production. PFAS are commonly produced through one of two processes—electrochemical fluorination or fluorotelomerization. The processes are dependent upon the manufacturer and the group of PFAS synthesized. For instance, perfluoroalkane sulfonic acids are only produced using electrochemical fluorination, while perfluoroalkyl carboxylic acids can be produced using either process (ITRC, 2020). Using either process, PFAS byproducts and residuals may result. The polymerization process to produce fluoropolymers may result in constituent components of the fluoropolymer and smaller “polymers” resulting from incomplete polymerization (Lohmann et al., 2020). Additionally, the polymerization process often uses PFAS, such as PFOA and PFNA, as processing aids, which can be left behind as residuals. PFAS byproducts and residuals are subsequently released into the environment via air emissions or wastewater streams (Lohmann et al., 2020). As one paper states, “Production of some fluoropolymers is intimately linked to the use and emissions of legacy and novel PFAS as polymer processing aids” (Lohmann et al., 2020). Processing aids have been substituted as scientific research continues to develop on legacy PFAS. For instance, Lohman et al. (2020) described how one producer substituted its use of PFOA for HFPO-DA as a processing aid for PTFE production. However, the legacy and replacement processing aids have similar chemical structures and similar environmental and human health concerns (described in **Section 4.4**).

> Industrial production of PFAS began around the 1930s with the number of unique chemicals and consumer products containing PFAS increasing over time (Dhore & Murthy, 2021). Replacement processing aids to substitute legacy compounds still have similar chemical structures and are still known as PFAS compounds.

Product Manufacturing. As previously discussed in **Section 4.1**, PFAS are known to be present in consumer products and used throughout industrial production. Their widespread application is due to their friction reduction, grease/oil repellence, nonstick properties, stain resistance, waterproofing, and similar properties. Product service lives can vary based on the product. For instance, disposal products (e.g., food packaging) have a short service life, while durable products (e.g., clothing) have long service lives.

Furthermore, PFAS-containing products that consumers purchase are not always intended to contain PFAS. The chemicals can result in consumer products through both intentional and unintentional addition. Reasons for PFAS resulting in a finished textile may include the following:

- Substances were intermediates or raw materials or unintentionally formed during production,
- Substances were intentionally used as part of the impregnating agent, and/or
- Substances were residues of processing aids from the production of fluoropolymers (Danish EPA, 2015; OECD, 2022a).

Notably, some manufacturers may also intentionally leave significant concentrations of non-polymeric PFAS in formulations to keep polymeric PFAS dispersed in the aqueous phase (OECD, 2022a).

The unintentional formation of substances during production has been cited in consumer products such as certain food packaging (Monge Brenes et al., 2019). Especially as PFOA and PFOS use continues to decline due to phase-outs across several manufacturers, low-level detections of PFOA and PFOS in packaging have brought attention to unintentional addition or formation. However, overall, there is a limited understanding of the presence of PFAS in products from intentional addition or as a byproduct of other processes (Joint Subcommittee on Environment, 2023).

SUSTAINABLE PACKAGING INDUSTRY VETERAN

During the manufacturing process of plastic packaging, PFAS, as processing aids, generally remain on the equipment. However, if PFAS do get transferred onto the product, it is more likely that they are embedded in between the layers of the plastic in very small amounts, rather than on the surface of the product.

EUROPEAN ACADEMIC FOCUSED ON PFAS

Products labeled as "PFAS-free" can become contaminated through shared production lines with products containing PFAS. Additionally, companies may report that their products are PFAS-free because they only consider the PFAS that are regulated or have different names, although more companies are adhering to OECD's PFAS definitions and standard naming schemes.

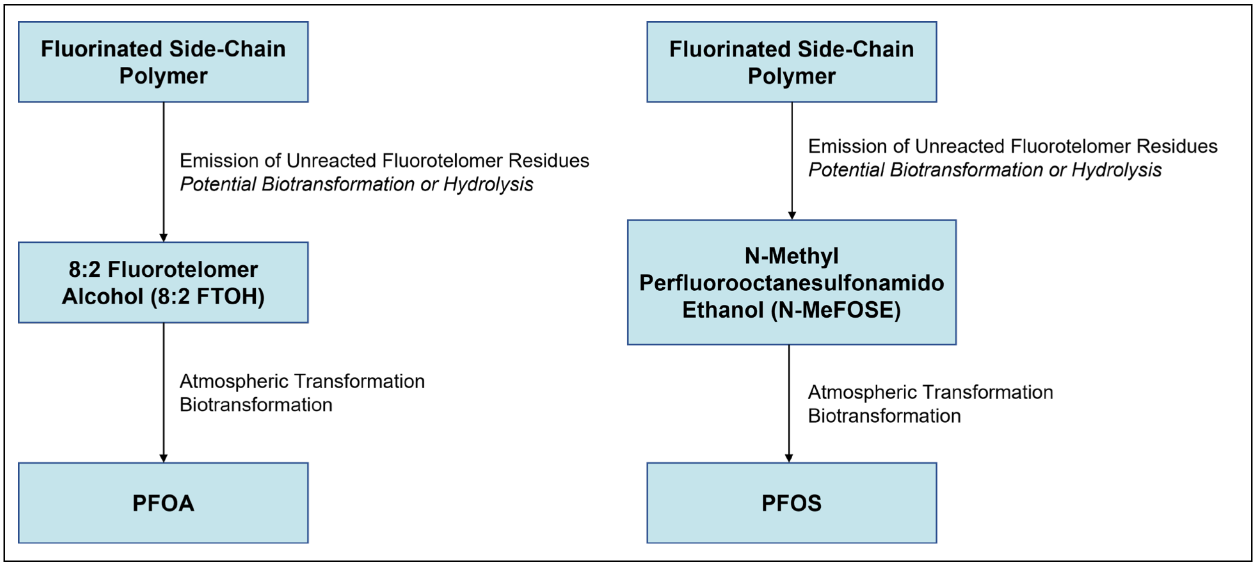
Product Labeling, Use, and Degradation Potential. Regardless of intentional or unintentional addition of PFAS in finished products, users may be exposed throughout the lifespan of the product due to usual wear and tear. Studies have discussed the degradation and formation of PFAS due to normal use and weathering of the products, as well as the leaching of PFAS. For example, side-chain fluorinated polymers can be released and can degrade into other PFAS.

RETAIL PACKAGING INDUSTRY VETERAN

PFAS contamination through manufacturing equipment when used as a processing aid is a new discovery. Before, it was something that people had never thought was occurring. The equipment usually comes with PFAS processing aids because suppliers understand how their equipment performs with certain materials and when these processing aids are needed.

The effects of elevated weathering conditions, including exposure to humidity, increased temperatures, and ultraviolet radiation have been reported for durable water-repellent clothing containing PFAS (specifically, clothing from a Swedish outdoor textile industry); the elevated weathering conditions were meant to be comparable to the lifespan of the outdoor clothing. Following weathering, most samples had increased concentrations of both ionic (e.g., PFHxA and PFOA) and volatile PFAS (e.g., 6:2 FTOH). Authors of this study hypothesized that the increased concentrations after weathering resulted from potential degradation pathways. For instance, the fluoropolymers originally present in the textiles for water repellence could form 6:2 FTOH and other volatile PFAS following weathering (Gremmel et al., 2016; van der Veen et al., 2020). Further weathering could then result in the formation of ionic PFAS (such as PFHpA and PFNA) and/or odd-chain length PFAS (such as PFUnA; Gremmel et al., 2016; van der Veen et al., 2020). More specifically, the authors provided examples of two transformations displayed in **Figure 4-5**.

Figure 4-5. Example Transformations of Fluorinated Side-Chain Polymers in Textiles.



From (Gremmel et al., 2016).

Leaching and Degradation. Lohman et al. (2020) also described the leaching of low molecular weight PFAS (i.e., processing aids or synthesis byproducts) from fluoropolymer products; however, the concentrations leached are highly dependent on the production and treatment processes. Considering the long half-lives of side-chain fluorinated polymers (and PFAS broadly), low molecular weight PFAS (e.g., PFOA and PFOS), released from the side-chains of polymers over time can contribute to long-term sources of non-polymeric PFAS (OECD, 2022a).

While Gremmel et al., (2016) focused on clothing, similar degradation and transformation is reported for other products using side-chain fluorinated polymers, including adhesives, food contact paper and paperboard, paints, and other textiles (Schwartz-Narbonne et al., 2023; OECD, 2022a). Regardless of product category, the use of side-chain fluorinated polymers can result in non-polymeric PFAS degradation products and impurities, which can further degrade (Schwartz-Narbonne et al., 2023; OECD, 2022a). For instance, a non-targeted analysis of molded "compostable" fiber bowls detected 6:2 FTOH, including transformation products of fluorotelomer unsaturated carboxylic acids (FTOHs; Schwartz-Narbonne et al., 2023).

Consumer products with polymeric PFAS can release PFAS degradation products throughout use and after the end of the product's usable life.

Users can be exposed to the degradation products directly during product use and indirectly as the degradation products are released in the air, solid waste, or wastewater.

Labeling. Generally, products are not required to label intentionally (or unintentionally) added PFAS. However, with the ever-increasing developments and research on PFAS-containing products and associated potential human health effects, some companies have chosen to label their products as "PFAS-free" or free of specific PFAS (i.e., "PFOA-free" and "PFOS-free"). Several consumer products (including apparel, bedding, and furnishings) used by children and adolescents with different product labeling—green assurances/certifications, water and/or stain resistance with or without trademarks, or no language regarding green assurances or water or stain resistance—were analyzed to determine the accuracy of the labels (Rodgers et al., 2022). A "green" label for products can be described as eco-friendly, chemical-free, nontoxic, or toxics free. However, green assurances were not indicative of whether PFAS were absent or present. Authors reported that products labeled as water and/or stain-resistant had more frequent detections and higher concentrations of the targeted PFAS, and therefore, that label—water- and/or stain-resistant—was more indicative of PFAS presence (Rodgers et al., 2022). Additionally, products labeled as "PFOA/PFOS-free" may still have detectable levels of other PFAS as evidenced in testing of PFOA-free pans and other PFOA/PFOS-free consumer products (Herzke et al., 2012; Schlummer et al., 2015).

Another study determined that PFAS were not listed in the ingredients for the majority of cosmetic products where PFAS were present (Whitehead et al., 2021). Authors suggested that PFAS were missing from the ingredients list due to PFAS used as bulking agents or colorants or PFAS being purchased under trade names that are then listed using a generalized name (Whitehead et al., 2021).

Notably, the EU has harmonized classification and labeling under the Classification, Labelling and Packaging Regulation; however, it only includes PFOA, ammonium pentadecafluorooctanoate (APFO), PFDA, PFHpA, and PFNA (ECHA, n.d.). Given the general lack of labeling requirements and potential for contamination, products labeled as "green" or "PFAS-free" are not necessarily accurate. Consumers may also be prone to look out for specific certified products. For instance, the label GreenScreen Certified indicates a product is free of PFAS and thousands of other chemicals of concern. OEKO-TEX is also an organic certifier that has issued a general ban on PFAS in footwear, leather, and textiles. However, as evidenced by the studies described, the certifications and labeling may not be accurate as it pertains to PFAS byproducts and contamination or use of PFAS alternatives.

End-of-Life Management. Once a product reaches the end of its service life, it is disposed of and managed via a variety of end-of-life pathways, including composting, landfilling, recycling, and thermal treatment. In 2020, the U.S. EPA published *Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances*, to provide information on three methods to destroy or dispose of PFAS-containing materials including 1) hazardous waste combustion (i.e., commercial incinerators), 2) hazardous waste or municipal solid waste landfills, and 3) deep well injection (U.S. EPA, 2020). High-temperature waste combustion, or thermal destruction, has emerged as a leading method for destruction of PFAS. However, studies have still reported less-than-complete destruction of PFAS at high operating temperatures (930–980°C or 1,706–1,796°F) (Liu et al., 2022; Solo-Gabriele et al., 2020). Destruction of PFAS requires injecting sufficient energy into the substance to break enough chemical bonds that the substance is converted into a more easily treatable substance. Energy can be added to break the carbon–fluorine (C-F) chemical bonds in PFAS through a variety of means including electrostatic discharge, microwaves, thermal, and ultrasound (Verma et al., 2022). The C-F chemical bond in PFAS is among the strongest known, so activating C-F decomposition is only possible at very high temperatures (~1,000–1,250°C or 1,832–2,282°F). In general, the chemical structure of PFAS play a large role in promoting destruction of the substance since the presence of non-fluorinated functional groups lowers the temperature required to break the C-F bond. Evidence suggests that temperatures required to initiate decomposition decrease as follows: perfluorocarbons > perfluoroacyl fluorides > PFSAs > PFCAs > perfluoroether carboxylic acids (Xiao et al., 2020).

However, there are still significant data and knowledge gaps associated with each of these destruction and disposal methods. For instance, there are plans to further evaluate emissions and their control efficiencies associated with hazardous waste combustion. Researchers have also noted the formation of PFAS byproducts and non-PFAS byproducts from different destruction methods (Horst et al., 2020).

Ultimately, current disposal methods, including incineration, landfilling, and wastewater treatment, may not completely destroy PFAS; rather the PFAS are transferred from one site to another. Stoiber et al. stated that “each disposal approach can return either the original PFAS or their degradation products back to the environment, illustrating that the PFAS problem is cyclical (Stoiber et al., 2020).” Municipal waste sent to landfills most likely include PFAS-based materials (i.e., PFAS-containing paints, varnishes, and sealants) and PFAS-containing products (i.e., food packaging and textiles). These materials can contribute to PFAS concentrations in landfill leachate, in addition to the concentrations in gas generation and landfill runoff. Studies have used simulated landfill reactors to observe leachate from PFAS-containing products and have demonstrated the waste composition-dependence of leached PFAS (Allredet al., 2015; Lang et al., 2017). Anaerobic microbiological degradation—similar to conditions within landfills—has been observed to enhance leaching of most classes of PFAS into landfill leachate from PFAS-containing municipal solid waste (Allredet al., 2015; Lang et al., 2017).

In addition to landfilling, in an attempt to reduce the volume of solid waste reaching landfills, some municipal waste is diverted to composting and recycling processes (Sivaram et al., 2022). PFAS, including PFOA, PFOS, and PFHxS, have been detected in composts, garden soils, and potting mixes commercially available (Bolan et al., 2021; Sivaram et al., 2022; Munoz et al., 2022). Food waste and food packaging (or FCMs) have been cited as sources of PFAS in compost with one study reporting composts containing food packaging to have the highest total

PFOA and PFOS level compared to composts that did not include compostable food packaging (Choi et al., 2019; Sivaram et al., 2022).

APPLICATION #2

General Product

Consider the lifecycle of the durable water-resistant rain jacket mentioned in Application #1.

Producers of PFAS, such as fluorinated side-chain polymers, supply the chemicals to manufacturers of the jacket. Manufacturers intentionally treat the products with the fluorinated side-chain polymers to impart water and stain resistance. However, residual PFAS may also be present.

Once distributed to retailers, the jackets are sold to consumers who use the product for a fixed lifetime. Throughout use of the jacket, the fluorinated side-chain polymers may degrade and release FTOHs, which can further degrade into PFOA.

Consumers may be directly exposed to PFAS from contact with the jacket or indirectly exposed to PFAS as it is released into indoor environments.

Following use, consumers may dispose of the jacket via municipal solid waste where any additional PFAS released contaminate the surrounding environment.

Similarly, biosolids (sewage sludge) produced from wastewater treatments can be contaminated with PFAS from domestic use of PFAS-containing products, including detergents, washing of clothes and other textiles, and others (Bolan et al., 2021; Munoz et al., 2022). Use of biosolids and other soil amendments like compost can result in PFAS entering the food chain through plant uptake, and subsequently, in fruits and vegetables consumed (Bolan et al., 2021; Sivaram et al., 2022). If PFAS are continually manufactured and used in products, then development of methods to treat or remove the compounds will be necessary (Stoiber et al., 2020).

Consumer Products with PFAS-Containing Recycled Materials. While not included in U.S. EPA’s Interim Guidance, PFAS-containing materials may also be disposed of or managed through recycling. Notably, PFAS are not removed during recycling, therefore, new products containing the recycled PFAS-containing content will inadvertently contain PFAS as well (Brunn et al., 2023; California Environmental Protection Agency, 2019). Recycling PFAS-containing materials ultimately contaminates secondary products. For example, the recycling of paper treated with PFAS can result in PFAS contamination of recycled paper (Brunn et al., 2023).

However, the recycling of PFAS-containing products, especially those with polymeric PFAS, is not well established or understood; fluoropolymers are often contaminated with other substances that make recycling difficult (Lohmann et al., 2020). The California Department of Toxic Substances Control noted that exposure to PFAS from carpet and food packaging can both occur through the products being made of recycled PFAS-containing materials (California Environmental Protection Agency, 2019). As a result, several state-level policies are restricting the ability to label PFAS-containing products as recyclable (see **Section 4.3.1**). However, while some states continue to permit the recycling of PFAS-containing products, further research is needed to understand the use of PFAS-containing recycled materials and potential consequences.

4.2 PFAS Commodity Market Trends

In 2020, the last year of reportable data, the United States manufactured or imported approximately 2.9 billion pounds of PFAS, only slightly less than the 3.2 billion produced in

2012.[6] In this section, we characterize the market for PFAS in four categories: supply, demand, trade, and releases. These categories encompass the key drivers of the total quantity of PFAS introduced within U.S. borders, which equals quantity domestically produced plus amount imported, minus amount exported. The resulting quantity of PFAS introduced within United States borders minus the amount released to the environment is embedded in goods produced for use in the United States or for export abroad. Estimating the quantity of PFAS in the U.S. economy and how it changes over time provides an indication of accumulating exposures.

We identified a total of 387 PFAS with known uses in industry from the data sources analyzed in this section. The CDR and Toxic Releases Inventory (TRI) data provide information on specific chemicals, however, only reporting of certain PFAS produced or released is required. For PFAS trade volumes, PFAS categories were identified in UNComtrade and USA Trade data using the HS of commodity codes, which does not provide information on specific PFAS chemicals. All datasets compiled and used for the analyses in this section can be found in the database (*PFAS Commodity Market Trends Database.xlsx*).

> The following section discusses market trends and contains static maps and tables.
> This information is also available on an interactive mapper located at https://bit.ly/pfasmarkettrends (RTI, 2023).

Much of the PFAS requiring reporting are non-polymers, so expectedly, many of the industry chemicals in CDR and TRI datasets were non-polymers (n = 305, 78.8%). Among the non-polymers that were further classified, fluorotelomer substances (n = 68, 17.6%) and perfluoroalkyl acids (n = 33, 8.5%) were the largest groups (**Table 4-6**). The following subsections assess the quantity of supply, trade, and releases along with the sources of demand for different PFAS categories in the United States.

KEY POINTS

- PFAS production activity is concentrated in the chemical sectors (NAICS 325).
- The United States manufactured or imported an average of 2.5 billion pounds of PFAS per year out of an average of 12.5 trillion pounds of chemicals produced in the United States per year. 2.5 billion pounds of PFAS is equivalent to approximately 8,160 fully loaded Boeing 747s.
- PFAS production and releases are predominantly in the eastern United States, from the Texas gulf coast north and east to Maine.
- Manufacturers of other chemicals and products comprise most PFAS demand.
- Polymers are the category of PFAS most actively traded internationally by the United States.
- Approximately 5 million pounds of PFAS were reported to be released into the environment between 2012 and 2021.
- Estimating the quantity of PFAS in the United States economy and how it is changing over time provides an indication of accumulating exposures.
- PFAS production has remained steady despite economic growth.
- Continued steady PFAS production will result in additional PFAS in consumer products and accumulation of PFAS in both the outdoor and indoor environment.

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[6] These estimates used the midpoint of the nationally aggregated production volumes reported in the CDR data.

Table 4-6. Summary of Categorization for PFAS Present in Industry

		Industry	
Classification	Category	N	(%)
Non-Polymers		305	(78.8)
Subclass	Perfluoroalkyl Substances		
Group	PFAAs	33	(8.5)
Group	FASAs	18	(4.7)
Group	Perfluoroalkane Sulfonyl Fluorides	10	(2.6)
Group	Perfluoroalkyl Ether Acids (PFEAs)	9	(2.3)
Group	Perfluoroalkanoyl Fluoride	6	(1.6)
Group	Perfluoroalkyl Iodides	6	(1.6)
–	Not Further Classified	77	(19.9)
Subclass	Polyfluoroalkyl Substances		
Group	Fluorotelomer Substances	68	(17.6)
Group	Perfluoroalkane Sulfonamido Substances	21	(5.4)
–	Not Further Classified	57	(14.7)
Polymers		77	(19.9)
Subclass	Side-Chain Fluorinated Polymers	64	(16.5)
Subclass	Fluoropolymers	12	(3.1)
Subclass	PFPE	1	(0.3)
Undetermined		5	(1.3)
Total		387	(100.0)

4.2.1 PFAS Domestic Supply

Facility-Level Information

Reporting Requirements. The TSCA CDR rule requires chemical-producing facilities to report to the EPA production volumes for certain PFAS they manufacture domestically or import into the United States. Reporting is required every four years and TSCA began requiring volume reporting in 2012. For the reporting years 2012, 2016, and 2020, facilities were required to report manufacturing and importing volumes separately. They were also asked to report a combined production volume (manufacturing and importing) for select previous years. Of the 1,410 PFAS listed on the TSCA inventory of chemicals, 354 PFAS were reported in the CDR data. Unfortunately, most of the CDR data at the facility level are classified as confidential business information (CBI), making it difficult to analyze production trends by facility.

Reporting Facilities. CDR data included 150 distinct domestic PFAS-producing facilities in the United States owned by 100 parent companies. The parent companies with the most PFAS facilities are DuPont de Nemours, Inc. (8 facilities), Honeywell International, Inc. (7 facilities), AGA Chemical, Inc. (5 facilities), and Chemours Co (5 facilities). Four facilities had their parent company listed as CBI. Some declared facility owners could be “special purpose vehicles” that obscured ultimate ownership by other parent companies.

Annual Facility Production. Facility-level reported production volumes varied widely from 0 pounds per year to over 100 million pounds. For manufacturing alone, the largest volume reported was 81,059,140 pounds of 2-chloro-1,1,1,2-tetrafluoroethane (CASRN 2837-89-0) by Honeywell International Inc.’s Geismar Complex in Geismar, Louisiana in 2012. In the most recent 2020 reporting cycle, Shin-Etsu Silicones of America, located in Freeport, Texas, reported the largest manufacturing volume at 1,500,000 pounds of 2,4,6-trimethyl-2,4,6-tris(3,3,3-trifluoropropyl)cyclotrisiloxane (CASRN 2374-14-3). The largest volume of a PFAS chemical being imported into the United States was reported by iGas USA Inc. of Tampa, Florida, at 20,092,688 pounds of pentafluoroethane (CASRN 354-33-6) in 2020.

Approximately 55% of the 150 total facilities listed their activity as an importer of PFAS, 25% of the facilities listed their activity as a manufacturer of PFAS, and just under 13% reported being both an importer and manufacturer of PFAS. Ten facilities provided no information, or their activity was listed as CBI. Of these 150 facilities, about one-third reported non-CBI production volumes, with the remainder claiming the numerical production volume quantities as CBI. **Table 4-7** shows reported facility-level production volumes separated by manufacturing and importing volumes for each PFAS category and year. Polyfluoroalkyl substances were the large majority (90%) of the manufacturing and importing volumes, followed by perfluoroalkyl substances (9%) and then polymers (1%). In total, facilities reported approximately 632 million pounds of PFAS being produced or imported in 2012, 2016, and 2020, for a yearly average of about 211 million pounds. However, these volumes do not include data that were classified as CBI. In a separate report, EPA combines the facility-level reported volumes, including CBI volumes, into nationally aggregated production volume ranges by chemical, which is further described in the “Nationally Aggregated Information” subsection.

Table 4-7. Yearly Facility-Level Production Volumes by PFAS Category (lbs.)

Production	2012	2016	2020
Perfluoroalkyl Substances			
Manufacturing	24,571,639	28,680,866	0
Importing	38,140	1,179,086	390,294
Production Volume	24,609,779	29,859,952	390,294
Polyfluoroalkyl Substances			
Manufacturing	254,533,348	218,270,395	1,539,123
Importing	11,641,516	36,432,904	51,438,141
Production Volume	266,174,864	254,703,299	52,977,264
Polymers			
Manufacturing	34,374	431,121	16,721
Importing	2,371,977	47,231	0
Production Volume	2,406,351	478,352	16,721
Total	293,190,994	285,041,603	53,384,279

Notes: Facility-level reported production volumes are a fraction of CDR’s national aggregate production volumes by chemistry because of CBI data claims. Using the midpoint estimate of national totals, the facility-level reported volumes vary widely as a fraction of their corresponding national totals, from 2.5% for polymers to 8.2% for perfluoroalkyl and 17.4% for polyfluoroalkyl substances.

Domestic manufacturing accounted for approximately 84% of PFAS production across the years. Facility-level reported manufacturing volumes declined by over 99% from 2016 to 2020;

however, this dramatic decline is only in facility-level data. As shown in **Table 4-7**, nationally aggregated volumes were essentially unchanged over 2012–2020 (discussed below). Reported facility-level import volumes increased by about 38% from 2016 to 2020. This was a result of an increase in polyfluoroalkyl substance importing; while the reported importing volumes for perfluoroalkyl substances and polymers declined in 2020. Looking at the data by PFAS category, perfluoroalkyl and polyfluoroalkyl substances had significantly higher manufacturing volumes compared to importing volumes, despite the low reporting in 2020. Conversely, the total reported polymer importing volume was about four times as large as the total reported polymer manufacturing volume.

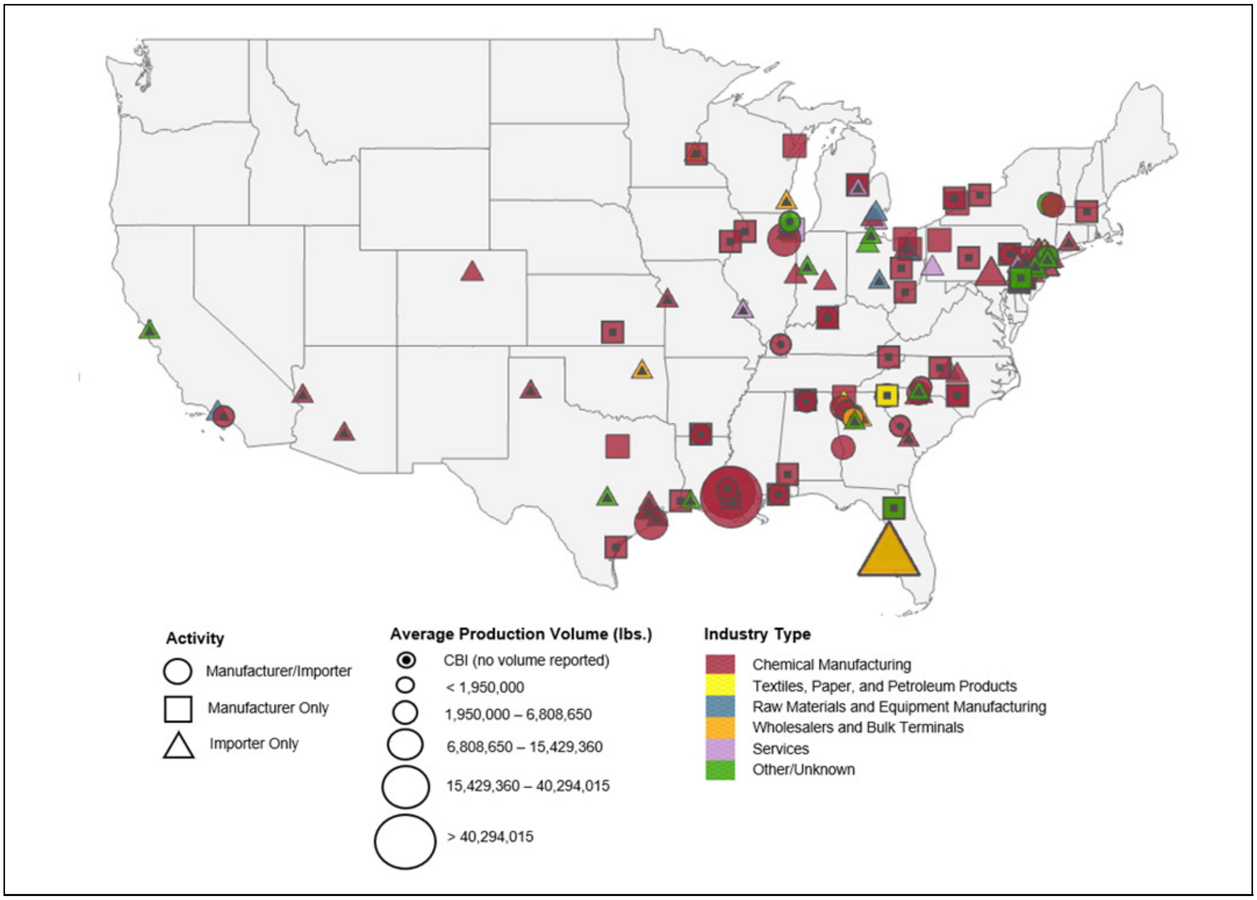
Although facility-level reported production volumes were significantly lower in 2020 compared to 2012 and 2016, this is most likely the result of increased CBI data claims. The 2020 reporting cycle was subject to the 2020 CDR Revisions rule and Small Manufacturer Definition Update rule, both published in the spring of 2020. These rule changes allowed more companies to be exempt from the need to report and added new byproduct reporting exemptions (U.S. EPA, 2022g).

In part because PFAS chemistry manufacturing processes may differ and facilities produce a variety of non-PFAS products, the facilities reporting CDR data identify under a variety of NAICS codes. Not being uniquely identified by any one NAICS code in economic data makes PFAS market characterization difficult. There were 40 facilities that reported their primary NAICS code in the 2020 CDR data, allowing us to connect their PFAS production to a reported NAICS code. The most frequently reported primary NAICS code in CDR, though not the largest by volume, was 325199 for “All Other Basic Organic Chemical Manufacturing,” reported by 14 facilities. This NAICS code is very broadly defined, capturing miscellaneous chemicals that do not fit as well in more narrowly defined subcategories of the broader 325 NAICS code. NAICS 325199 includes chemicals ranging from biodiesel to silicone to artificial sweeteners (U.S. Census Bureau, 2022).

As described in the methods, we merged NAICS information using the Facility Registry Service ID and the Industrial Sector code to identify NAICS codes for an additional 88 facilities that did not report a NAICS code in the 2020 CDR data, resulting in a total of 128 facilities with NAICS codes. We were not able to identify NAICS codes for 22 facilities. About 75% of these 128 facilities reported at least one NAICS code within the 325 sector for Chemical Manufacturing, with the next largest being 9% of facilities which reported the 424 sector for Merchant Wholesalers.

Figure 4-6 shows the PFAS-producing facilities by location with the facility’s activity designated by shape and NAICS code groupings indicated by color**.** For the one-third of facilities that reported non-CBI production volumes, the marker size indicates average yearly production volume. The other two-thirds of the facilities were given a standard size with a “dot” to distinguish these facilities from those that have known information about the amount of PFAS produced at that facility. The 150 PFAS-producing facilities identified in the CDR data were mostly concentrated in the eastern half of the continental United States. Only six PFAS-producing facilities were west of Texas; one in Colorado, two in Arizona, and three in California. In general, specific industry sectors were not located in any one area or region. However, PFAS-producing facilities within the “Services” industry sector were predominantly in the Northeast and facilities within the Wholesalers or Bulk Terminals sector that reported importing PFAS appear to be mostly concentrated in locations near the coast.

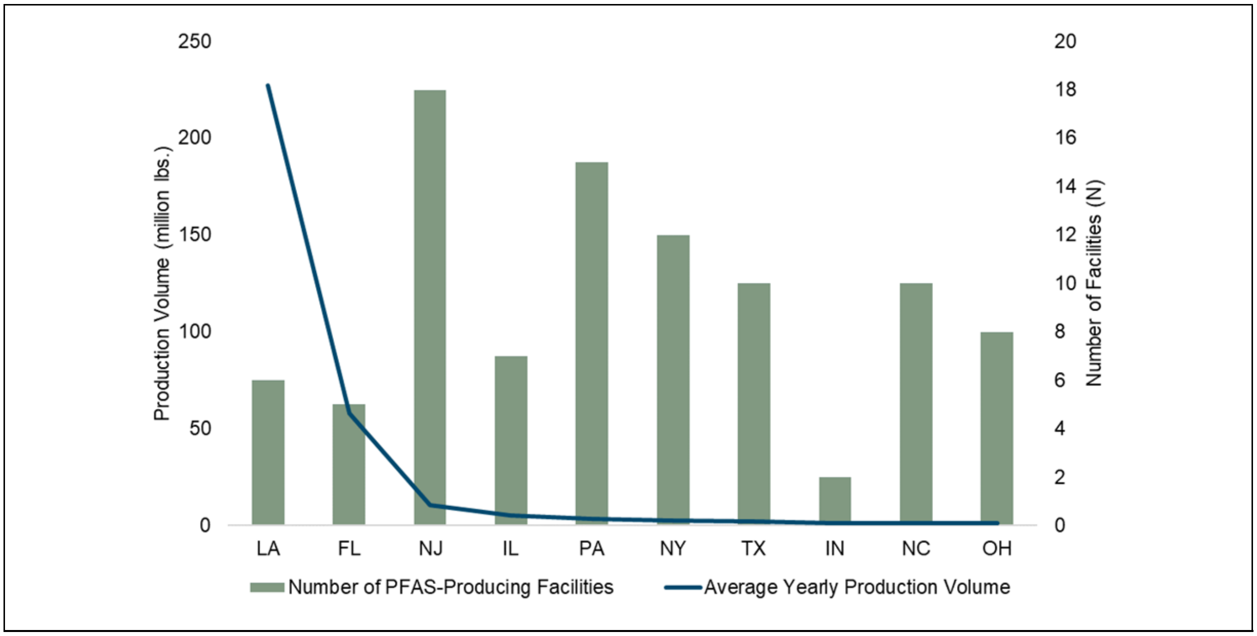
Figure 4-6. Spatial Distribution of Domestic PFAS-Producing Facilities (2012–2020)



Data Source: CDR.

There was an average of three facilities per state with a range from 0 to 18 facilities, and an average yearly reported production volume of approximately 6 million pounds per state, ranging from zero to just over 227 million pounds. The area between Ohio, Pennsylvania, New Jersey, and southern New York had the highest density of PFAS-producing facilities, with 53 facilities in these four states alone. The southeast also had concentrated PFAS-producing facilities spread across Georgia, North Carolina, South Carolina, Alabama, Louisiana, and Florida. Despite having a smaller number of facilities, the two states with the largest reported production volumes were Louisiana, with an average yearly volume of 227,046,187 pounds, and Florida, with an average yearly volume of 58,091,911 pounds (**Figure 4-7**). In Louisiana, over 80% of this production volume was reported by Honeywell International Inc – Geismar Complex. This facility reported both manufacturing and importing PFAS. In Florida, the two companies responsible for the large amount of PFAS production were iGas USA, inc. and BMP International, inc., which both reported only importing PFAS. Comparatively, the production volumes in the other states were significantly lower, which may be due to other large companies claiming CBI.

Figure 4-7. Ten States with the Largest Average Yearly PFAS Production Volume (2012–2020)



Data Source: CDR.

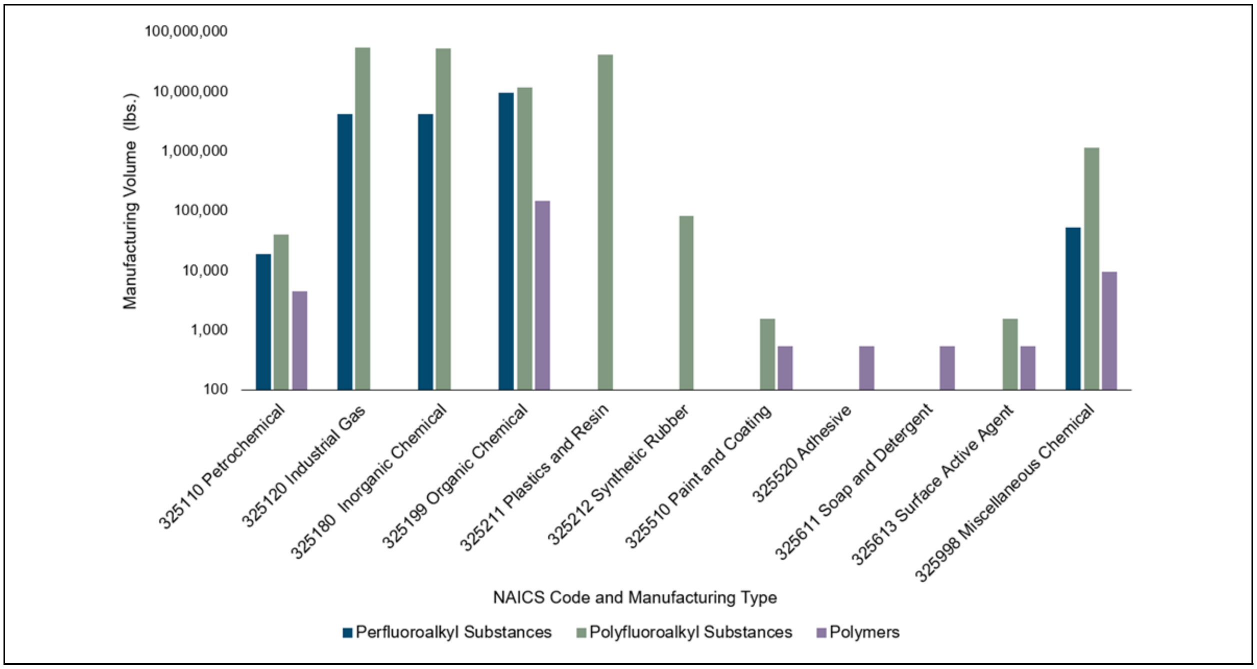
To assess PFAS production trends at the industry level, we aggregated facility-level manufacturing and importing volumes by NAICS code for each reporting year with volume data (2012, 2016, and 2020). Much like PFAS final uses being broadly spread throughout consumer and other final products, PFAS manufacturing is broadly spread throughout chemical sectors. Identifying where in the economy PFAS are manufactured helps us estimate how production volumes, associated contamination risk, and the stock of PFAS in consumer and other products may change over time with economic growth. As described in the methods, only 325 sector NAICS codes were considered for manufacturing volume trends. The volumes were summed at the facility-level and averaged across the three years by NAICS code. Eleven NAICS codes were associated with the manufacturing of PFAS, as shown in **Table 4-8**. The average yearly reported manufacturing volume of approximately 175 million pounds was predominantly split between the NAICS codes for 325102 – Industrial Gas Manufacturing (32.4%), 325180 – Other Basic Inorganic Chemical Manufacturing (31.5%), and 325211 –Plastics Material and Resin Manufacturing (23.2%).

When considering the manufacturing volume by industry type and PFAS category, we see that the industries with the largest volumes are predominantly manufacturing polyfluoroalkyl substances (**Figure 4-8**). The facilities represented by 325102 – Industrial Gas Manufacturing, 325180 – Other Basic Inorganic Chemical Manufacturing, and 325998 – All Other Miscellaneous Chemical Product and Preparation Manufacturing reported approximately 93% polyfluoroalkyl substances manufacturing, 7% perfluoroalkyl substances manufacturing and 0% polymers manufacturing. The NAICS code with the third largest manufacturing volume, 325211 – Plastics Material and Resin Manufacturing, only had polyfluoroalkyl substances reported. Facilities within the 325199 - All Other Basic Organic Chemical Manufacturing industry reported a more even distribution, manufacturing 44% perfluoroalkyl substances, 55% polyfluoroalkyl substances, and 0.7% polymers. In the 325520 – Adhesive Manufacturing and 325611 – Soap and Other Detergent Manufacturing industries, facilities only reported manufacturing small amounts of polymers.

Table 4-8. Average Manufacturing Volumes by Industry Type (2012–2020)

NAICS Code	Title	Average Manufacturing Volume (lbs.)	(%)
325110	Petrochemical Manufacturing	62,167	(0.04)
325120	Industrial Gas Manufacturing	57,094,979	(32.4)
325180	Other Basic Inorganic Chemical Manufacturing	55,519,573	(31.5)
325199	All Other Basic Organic Chemical Manufacturing	21,166,176	(12.0)
325211	Plastics Material and Resin Manufacturing	40,907,737	(23.2)
325212	Synthetic Rubber Manufacturing	80,964	(0.1)
325510	Paint and Coating Manufacturing	2,031	(0.0)
325520	Adhesive Manufacturing	525	(0.0)
325611	Soap and Other Detergent Manufacturing	525	(0.0)
325613	Surface Active Agent Manufacturing	2,031	(0.0)
325998	All Other Miscellaneous Chemical Product and Preparation Manufacturing	1,176,771	(0.7)
Total Average Manufacturing Volume		**176,013,483**	(100.0)

Figure 4-8. Average Manufacturing Volumes by Industry Type and PFAS Category (2012–2020)



Data Source: CDR.

Nationally Aggregated Information. In the CDR data, TSCA also reports nationally aggregated production volumes by chemical for the years 2012, 2016, and 2020, using the facility-level reported production volumes. As described in the methods, aggregated volumes are a mix of single values and ranges depending on whether facilities reported the facility-level production volume estimates as CBI for that chemical. For the production volumes reported as ranges, most stayed consistent across the years. However, the ranges for two PFAS differ drastically between 2012 and 2020 compared to 2016. The perfluoroalkyl substances 1,1,1-Trichloro-2,2,2-trifluoroethane (CASRN 354-58-5) and 1,1,2-Trichloro-1,2,2-trifluoroethane (CASRN 76-13-1) had ranges of 100 million to under 1 billion pounds in 2012 and 2020 but only had a range of 20–100 million pounds in 2016. The large maximum production volume significantly increases the total nationally aggregated production volume in 2012 and 2020. Similarly, the production volumes reported as point values fluctuate by year, with some chemicals increasing in production and some decreasing.

National volumes are an order of magnitude larger than the facility-level totals as shown in **Table 4-9**. In total, when using the midpoint of the reported range for each chemical, the publicly available facility-level production volumes are less than 10% of all production volumes reported to EPA. Compared to the facility-level production volume trends, the nationally aggregated production volume in 2020 is only slightly less than the nationally aggregated production volume for 2012 and is greater than the volume in 2016. This suggests that the 2020 facility-level reported production volumes were significantly impacted by the 2020 rule changes mentioned above and include increased CBI data claims, with approximately only 2% of the total volume reported as non-CBI values.

Table 4-9. Facility-Level and Nationally Aggregated Total PFAS Production Volumes by Year

Year	Facility-Level Volume (lbs.)	Estimated Nationally Aggregated Volume (lbs.) (Midpoint)	Facility-Level Volume as a Percentage of Estimated Nationally Aggregated Volume (%)
2012	293,190,994	3,163,038,064	9.3
2016	285,041,603	1,597,087,646	17.9
2020	53,384,279	2,857,464,230	1.9

Nationally aggregated PFAS production volumes reported in the CDR data have not shown growth over the past ten years, consistent with the broader chemicals industry (i.e., NAICS 325). While output for the broader chemicals sector has been largely steady over the past decade with a compound annual growth rate (CAGR) of 0.1%, CDR-reported PFAS volumes have declined by -1.3% in total with perfluoroalkyl substances falling –2.7% and polyfluoroalkyl substances and polymers rising by 1.2% and 4.3% per year, respectively (midpoints in **Table 4-10**). That is, the chemicals sector has grown slower than the entire economy over the past decade and, within that, CDR national aggregate volume data suggest PFAS production has grown slower still.

Table 4-10. Nationally Aggregated Production Volume Ranges by PFAS Category (lbs)

Category	Value	2012	2016	2020	CAGR
Perfluoroalkyl Substances	Mid	1,933,119,835	472,009,305	1,464,616,010	–3.4%
	Min	347,419,835	108,809,305	268,928,510	–3.2%
	Max	3,518,819,835	835,209,305	2,660,303,510	–3.4%
Polyfluoroalkyl Substances	Mid	1,207,008,196	1,102,061,471	1,357,831,499	1.5%
	Min	642,658,196	565,348,971	585,393,999	–1.2%
	Max	1,771,358,196	1,638,773,971	2,130,268,999	2.3%
Polymers	Mid	22,910,033	23,016,870	35,016,721	5.4%
	Min	372,533	479,370	1,016,721	13.4%
	Max	45,447,533	45,554,370	69,016,721	5.4%
Total	Mid	3,163,038,064	1,597,087,646	2,857,464,230	–1.3%
	Min	990,450,564	674,637,646	855,339,230	–1.8%
	Max	5,335,625,564	2,519,537,646	4,859,589,230	–1.2%

Notes: CAGR is calculated as the 2020 value divided by the 2012 value raised to the (1/8), minus one.

4.2.2 PFAS Domestic Demand

While PFAS have permeated nearly every part of the economy, direct handling of PFAS post-manufacturing may be more limited to certain sectors. We evaluated the dollar value of purchases from PFAS-producing sectors by other sectors of the economy using BEA input-output use tables and found that nearly half (46%) of output from PFAS-producing sectors is purchased by other chemical sectors (NAICS 325) and 80% is purchased by what are generally referred to as “manufacturing sectors” in economic contexts (NAICS 31-33). By contrast, only 14% of output from PFAS-producing sectors is purchased by sectors with NAICS codes 34 and above—sectors that sell larger fractions of their output for final uses (e.g., by consumers) such as services and information sectors. Data limitations mean that these patterns of inter-industry purchases can offer only an approximate indication of PFAS transactions in the economy as sales data from PFAS-producing industry comprise both PFAS and non-PFAS commodities.

We constructed a demand index based on the distribution of PFAS manufacturing over PFAS-producing sectors and the sources of demand for these sectors. We established the proportion of demand for PFAS-producing sectors coming from each NAICS (3-digit) sector to weight the historical output of each sector. The demand index shows that the sources of potential PFAS demand have changed over the past decade, with little change in the first five years since 2012 and approximately 20% growth in the past five years or a CAGR of 3.7%. The growth in potential PFAS demand against the negligible growth in the amount of chemicals produced and apparent decline in PFAS supply could be a result of several factors. Our demand index is an imperfect proxy for actual PFAS demand. We cannot evaluate all factors contributing to the misalignment of our demand index

> The domestic demand patterns suggest that direct PFAS use may largely be by producers of intermediate goods implying that producers of consumer products are more likely to purchase PFAS embedded in intermediate materials such as textiles.

with actual PFAS demand, but factors could include changes in the chemical efficiency of demand sectors, costs of chemical production and/or production of non-PFAS by PFAS-producing sectors. More details on the demand index can be found within **Section 4.2.5** below**.**

4.2.3 PFAS International Trade

Trade Volume Spatial Trends

While economic accounts report that approximately 20% of PFAS-producing sectors' output is exported, trade data indicate that only a small fraction of that may be PFAS (BEA, 2023). Trade data record annual international commodity flows in value and, in many cases, physical quantities under HS codes. While HS codes offer greater commodity specificity than NAICS codes, identifying PFAS remains a challenge. HS code definitions do not include specific CASRNs and/or chemical identifiers; HS codes vary in specificity with some codes pertaining to only a single chemical, while others pertain to a subclass or group of chemicals. Therefore, it is unclear how comprehensively the identified HS codes cover trade in PFAS, especially chemicals that are lesser studied. The number of PFAS-related HS codes we identified varied by PFAS category: 20 HS codes covering perfluoroalkyl substances (15 of which were added in the past five years), six HS codes for polyfluoroalkyl substances, and two for polymers.

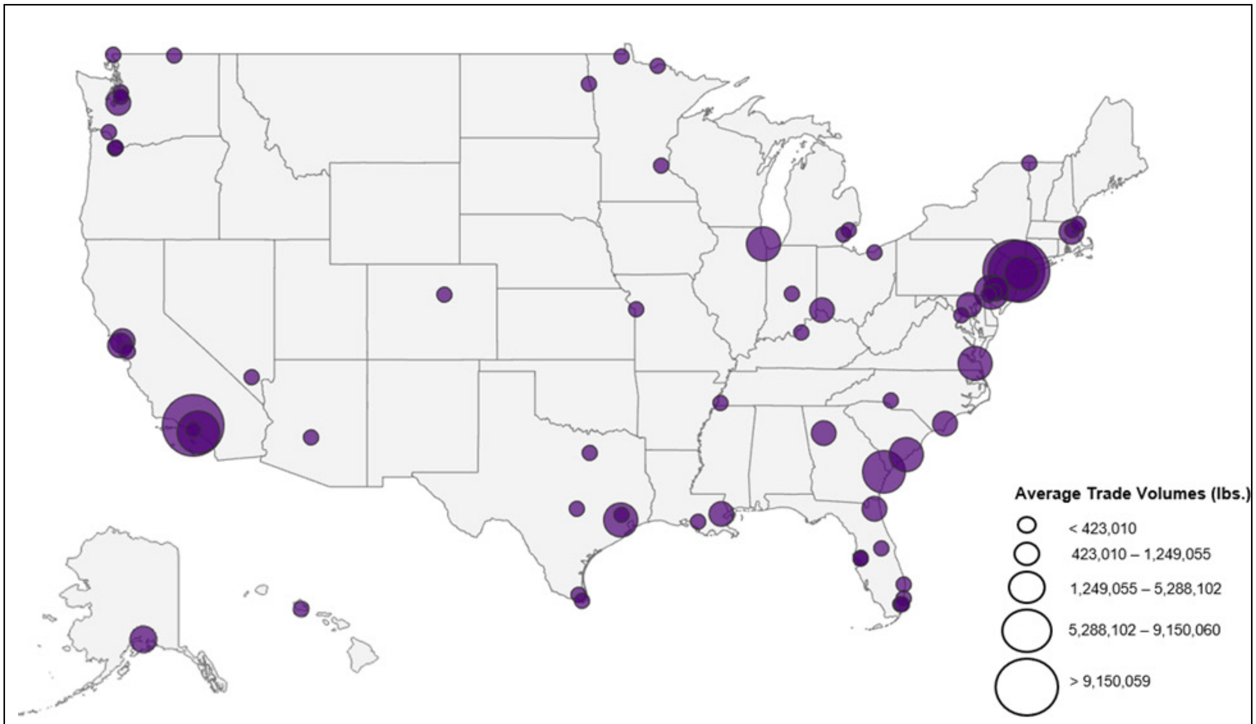
Import volumes by PFAS category reported in UN Comtrade data for perfluoroalkyl substances and polyfluoroalkyl substances are comparable in order of magnitude to facility-level import volumes reported in the CDR data, but polyfluoroalkyl substances (10–50 million pounds in both datasets over the past decade) trend in opposite directions (rising steadily in CDR and declining in UN Comtrade). Perfluoroalkyl substances show a significant rise in UN Comtrade data in 2022, which is not reported in CDR. The data limitations of both data sources likely contribute to the divergence between CDR and UN Comtrade data (see **Appendix C** for more information).

In total, international trade in HS-code-identified PFAS commodities is on the order of 100 million pounds per year, or approximately 4% of CDR national average production volumes (imports plus manufacturing) of 2.5 billion pounds per year, significantly less than the chemicals industry (29% for NAICS 325) and less than the overall economy (7%) as of 2021 (BEA, 2023). These relative quantities suggest that international trade is not a major factor in domestic PFAS markets.

International PFAS shipments are exported or imported to the United States via air, water, rail, and road transport, with the largest quantities passing through marine ports on the East, Gulf, and West coasts. **Figure 4-9** shows average total trade volume, equal to imports plus exports, for 2016 by port of entry/exit. Like the geographic distribution of PFAS manufacturing facilities, PFAS total trade volumes exhibit a high concentration in the northeastern United States, including eastern Pennsylvania, southern New York, and New Jersey.

> International PFAS shipments can enter and leave the United States via air, water, rail, and road transport, although the largest quantities enter via marine ports on the East, Gulf, and West coasts

Figure 4-9. Spatial Distribution of Port-level PFAS Trade Volumes (2016)



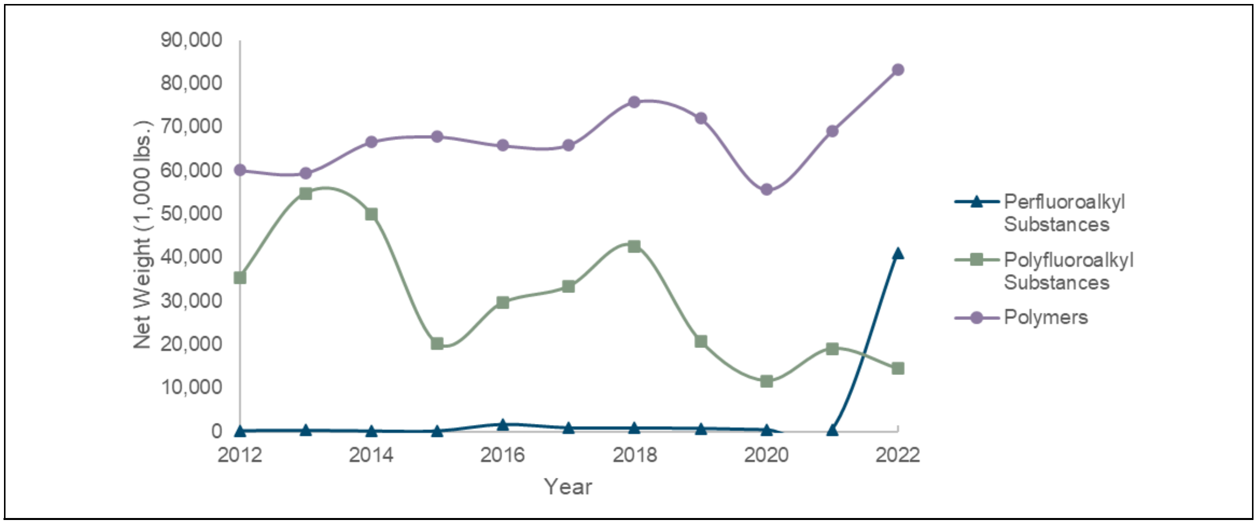
Data Source: USA Trade.

Trade Volume Temporal Trends

Figures 4-10 and **4-11** show UN Comtrade PFAS import and export volumes by PFAS category, respectively. Polymers show robust trade volumes with over 83 million pounds of annual imports and over 78 million pounds of annual exports over the past decade. Comparatively, the total trade volumes of polyfluoroalkyl substances, as identified in HS codes, are minimal with polyfluoroalkyl substances exhibiting marked declines for both imports and exports. On the other hand, perfluoroalkyl substances exhibit a rather significant increase for both imports and exports in 2022 after dropping near to zero during the coronavirus disease 2019 (COVID-19) pandemic; however, this is likely due to the latest HS code edition released for 2022. Most HS codes included for perfluoroalkyl substances were added in the new addition.

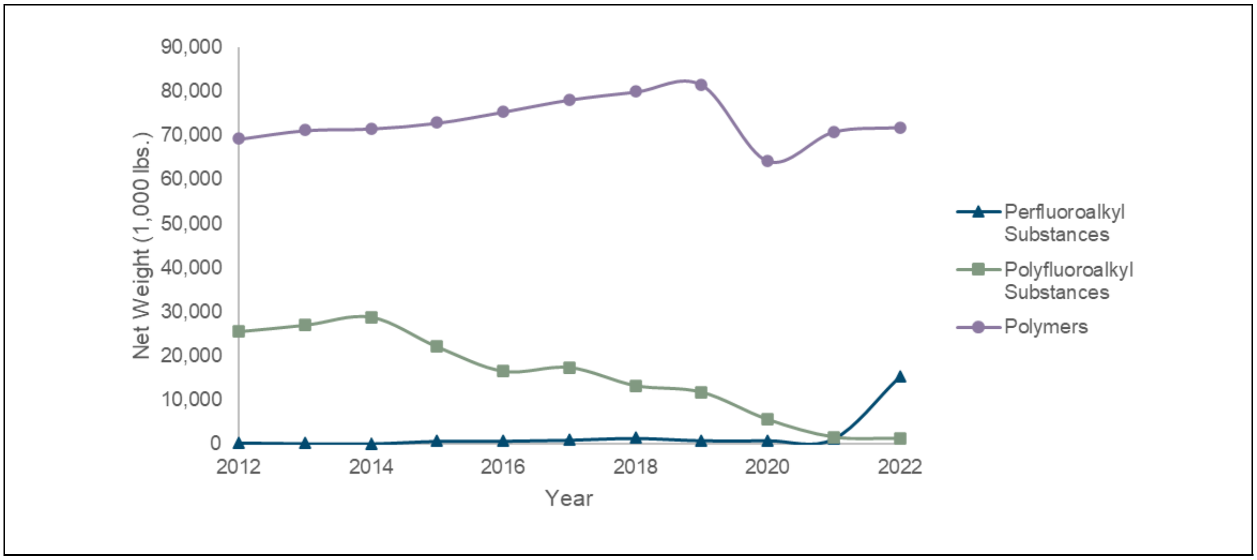
It may be that the United States supply for perfluoroalkyl substances and polyfluoroalkyl substances is predominantly manufactured and demanded domestically given what chemistries are observable under HS codes. However, as noted previously, the HS codes are limited in their descriptions and dependent on the trade of previous years. With evolving HS code editions, there may be changes in how PFAS are reported, and therefore, corresponding changes to how the trade volumes appear by PFAS category. Further research is required to exhaustively identify as many PFAS as possible throughout the HS system.

Figure 4-10. Net Weight (1,000 lbs.) Imported by PFAS Category



Data Source: UN Comtrade.

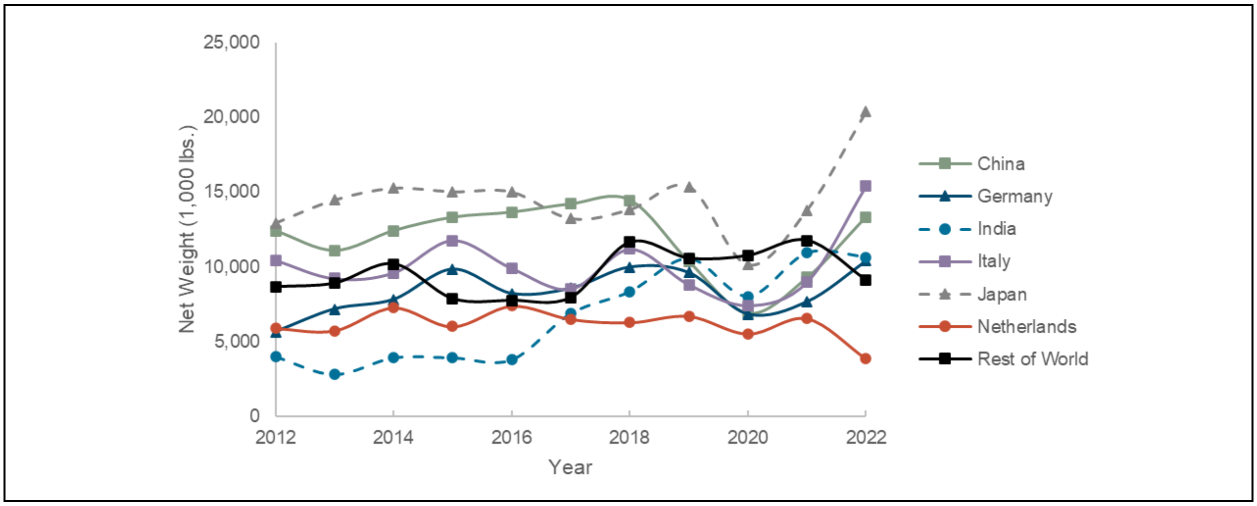
Figure 4-11. Net Weight (1,000 lbs.) Exported by PFAS Category



Data Source: UN Comtrade

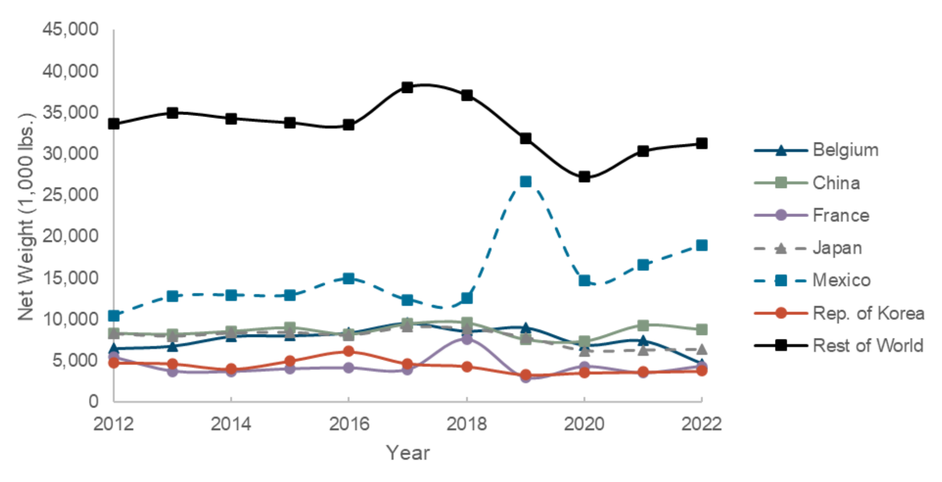
Due to changes in the HS code editions affecting the import and export volumes exhibited for perfluoroalkyl substances and polyfluoroalkyl substances, only the trade of polymers is further summarized. (See **Appendix C** for more information on the trade of perfluoroalkyl substances and polyfluoroalkyl substances.) Given the significant quantities imported or exported for the HS codes categorized in polymers, trade volumes by country are shown in **Figures 4-12** and **4-13**. Countries that contributed less than 5% of the total United States trade volume over the period are grouped as “rest of world.” Over the period, Japan has been the largest source of United States PFAS imports, whereas the “rest of world” group has been the largest destination for exports of polymers suggesting that the United States has a diverse network of trading partners in polymers. Excluding the “rest of world” group, Mexico is the largest trading partner for exports of polymers.

Figure 4-12. Net Weight (1,000 lbs.) Imported for HS Codes Associated with Polymers



Data Source: UN Comtrade.

Figure 4-13. Net Weight (1,000 lbs.) Exported for HS Codes Associated with Polymers



Data Source: UN Comtrade.

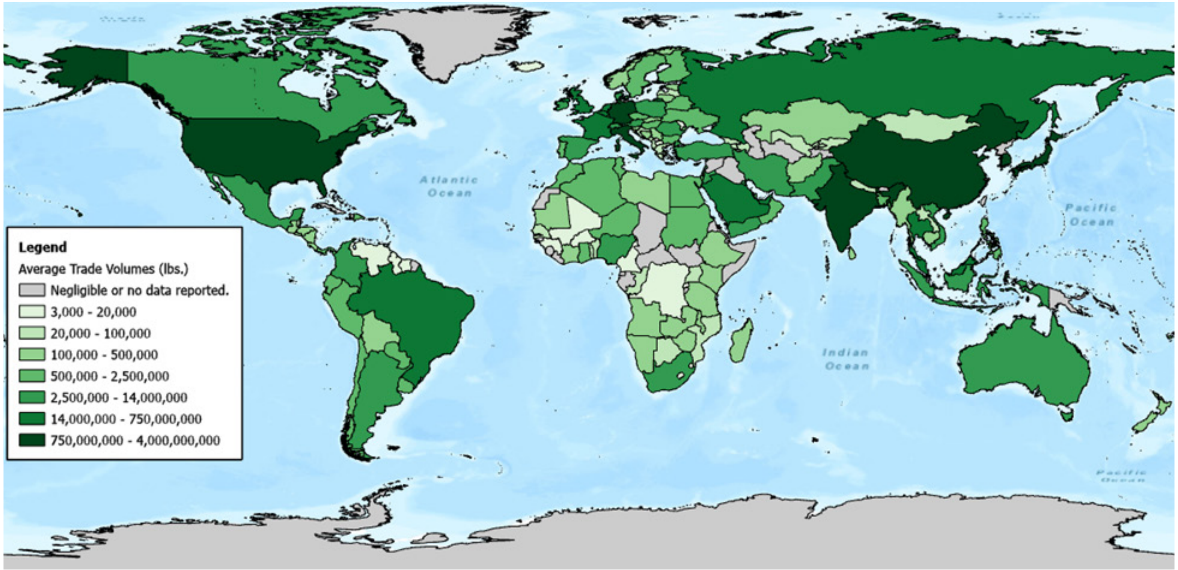
Global Trade Patterns

Using the 2020 CDR data and targeted literature searches, we identified at least 121 foreign company groups that are producing PFAS internationally and may be importing PFAS into the United States. It is important to note that this list is not comprehensive and there are likely many other companies across the world producing and importing PFAS. On our list, we identified the country of the company group headquarters as well as the countries where there are known facilities producing PFAS. Germany had the most company group headquarter locations (29), followed by China (13), and Japan (12). There were also 15 company groups headquartered in the United States, including 3M, Chemours, DuPont, and Honeywell International, that had

PFAS-producing facilities in the United States as well as in other countries (mostly centralized in Europe and China).

Examining global trade patterns, UN Comtrade country-level reporting of import and export volumes of PFAS HS codes (identified above) with the world reveals relatively few countries not reporting PFAS trade volumes (**Figure 4-14**). Globally, China leads the world in PFAS trade volume followed by the United States, Germany, Japan, and India. These five countries reported the largest average annual trade volumes (imports plus exports) during the time frame 2012–2021, with their values ranging from around 80 million pounds (India) to 400 million pounds of PFAS (China). Reported global PFAS trade averages approximately 450 million pounds per year over the period (i.e., the average of total imports and exports, which should match theoretically but do not given data limitations).

Figure 4-14. Average PFAS Total Trade Volumes (lbs.) by Country (2012–2021)



Data Source: UN Comtrade.

4.2.4 PFAS Releases Reported to the U.S. EPA

Releases by PFAS-Producing Facilities

The TRI compiled and maintained by the U.S. EPA tracks the releases of certain chemicals that may pose a threat to human health or the environment, by requiring the annual reporting of how much of each chemical is released to the air, land, or water. TRI only requires specific industries to report releases and does not capture PFAS releases that impact select populations, such as at military bases. Of the 787 unique chemicals on the TRI toxic chemical list, we identified 68 PFAS that were reported as releases, many of which overlapped with the chemicals reported in the CDR data. Seventeen PFAS-producing facilities also reported onsite PFAS releases to TRI between 2012 and 2021. The largest air release was 117,640 pounds of 2-chloro-1,1,1,2-tetrafluoroethane by Honeywell International Geismar complex in Geismar, Louisiana in 2014. This facility also released similar amounts in the years 2012–2015. Chemours Washington Works in Washington, West Virginia, had the largest water release at 673 pounds of hexafluoropropylene oxide dimer acid ammonium salt in 2021, and it also had the largest land release at 96,100 pounds of tetrafluoroethylene in 2012. Over 80% (548/671) of the reported releases were attributable to four parent companies: Honeywell International Inc., Chemours Co., 3M Co., and Daikin America Inc.

We also tabulated the PFAS chemical releases by TRI Industry Sector for each year (**Table 4-11**). The TRI industry sector is based off the first three or four digits of the facility's NAICS code and is reported directly in the TRI data. Four industries were represented by the PFAS-producing facilities with releases, including Chemical Manufacturing, Plastics and Rubber, Machinery, and Chemical Wholesalers. The facilities within the Chemical Manufacturing industry had the most releases, accounting for almost 95% of the total volume of releases in pounds. Generally, across all industries, the volume of PFAS reported releases has declined between 2012 and 2021. The cumulative amount of PFAS releases reported to TRI by PFAS-producing facilities was over 3.9 million pounds from 2012 to 2021, which is likely an underestimate given that only certain PFAS chemicals are required to be reported and just 17 of the 150 facilities reported releases during this period.

Releases by All Facilities

Between 2012 and 2021, an additional 72 facilities that were not identified as PFAS-producing facilities in the CDR data also reported onsite PFAS releases to TRI. It is likely that these were a mix of PFAS-using facilities as well as facilities managing chemical waste. The 17 PFAS-producing facilities accounted for approximately 80% of the total volume of onsite PFAS releases, with 20% of the volume reported by the other 72 facilities, for a total cumulative volume of 5 million pounds between 2012 and 2021. Of the total amount reported to be released, 95% was released to the air, 4% was released to the land, 0.02% was released to the water, and the remaining almost 1% was unknown.

> To put 5 million pounds of PFAS releases into perspective, a fully loaded Boeing 747 can carry a payload of 306,443 pounds. Cumulative PFAS releases reported to TRI from 2012-2021 were equivalent to more than 16 fully loaded Boeing 747s, while the health effects from PFAS are measured on a much smaller scale down to parts per trillion.

When assessing all 89 facilities with reported PFAS releases, perfluoroalkyl substances accounted for 65% of releases, followed by polyfluoroalkyl substances at 35%. Polymers were only recently required to be reported to TRI in 2020 and made up 0.4% of the total volume reported in 2020-2021. **Figure 4-15** shows the trend of releases by PFAS category from 2012 to 2021. Both the perfluoroalkyl and polyfluoroalkyl substances show a general decline across the years.

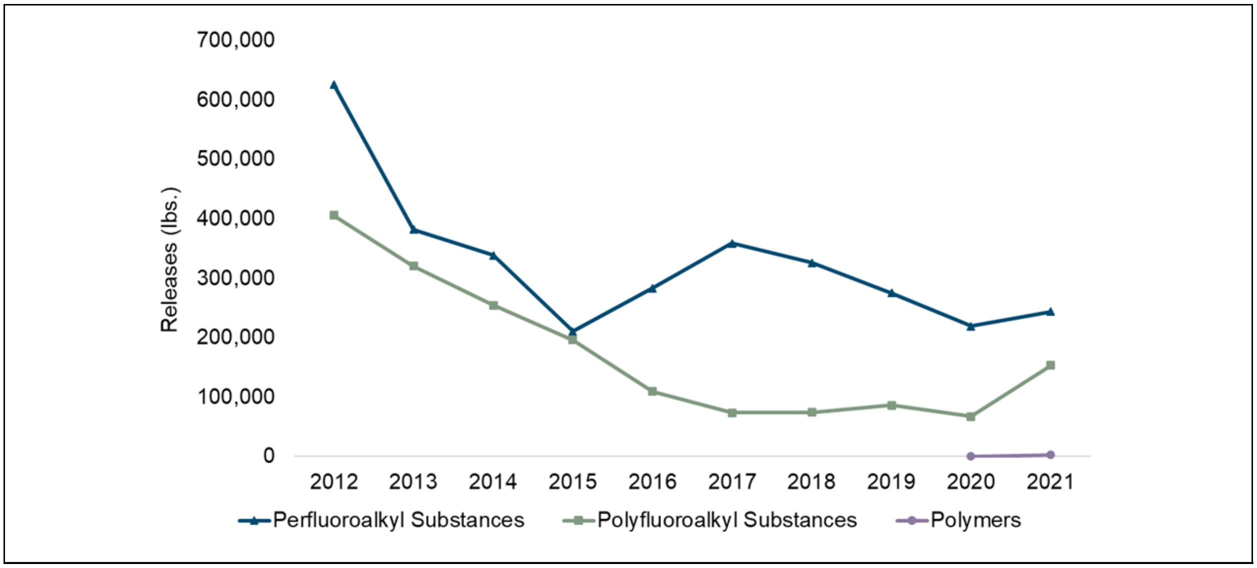
The additional 72 facilities reporting PFAS releases represented nine new TRI industry sectors for a total of 14 sectors across all 89 facilities. The five sectors with the largest average yearly onsite PFAS releases across all facilities included Chemicals, Miscellaneous Manufacturing, Plastics and Rubber, Hazardous Waste, and Computer and Electronic Products, as shown in **Figure 4-16**. Facilities in the Chemical sector reported approximately 80% of the total volume of PFAS releases. PFAS releases by non-chemical production facilities indicated some of the major PFAS-using sectors. Consistent with the potential PFAS-using sectors identified in the PFAS Domestic Demand subsection above, PFAS releases outside the chemical sector were largely by manufacturing sectors. There was also a small percentage (2%) of PFAS releases by facilities handling chemical waste in the Hazardous Waste sector. This was the only sector that reported releases of all three categories of PFAS.

Table 4-11. Onsite PFAS Releases by Industry Sector for PFAS-Producing Facilities

TRI Industry Sector	PFAS Releases (lbs.) for Each Reporting Year									
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
325 Chemicals	531,222	399,802	395,529	340,048	367,102	421,570	386,971	345,561	245,256	284,682
326 Plastics and Rubber	46,736	62,152	80,012	0	–	–	–	–	–	13,578
333 Machinery	–	–	–	–	–	–	–	–	–	750
4246 Chemical Wholesalers	31	22	–	–	115	276	99	0	0	0
Total	577,989	461,976	475,541	340,048	367,217	421,846	387,070	345,561	245,256	299,010

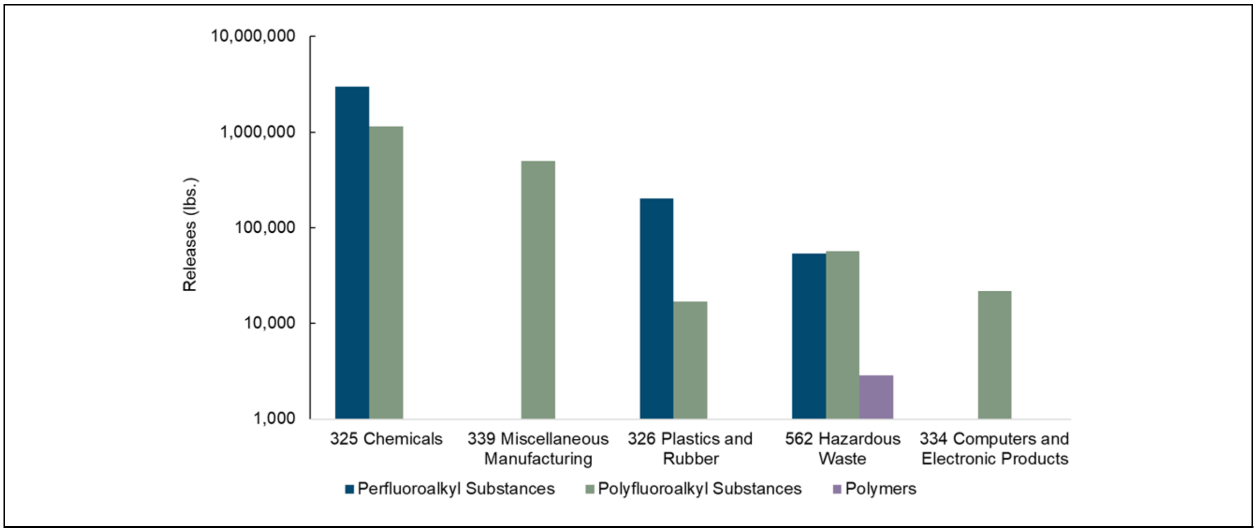
Note that “–“ means no data were reported during that year.

Figure 4-15. Onsite PFAS Releases by PFAS Category (2012–2021)



Data Source: TRI.

Figure 4-16. Sectors with the Largest Average Yearly Onsite PFAS Releases (2012–2021)

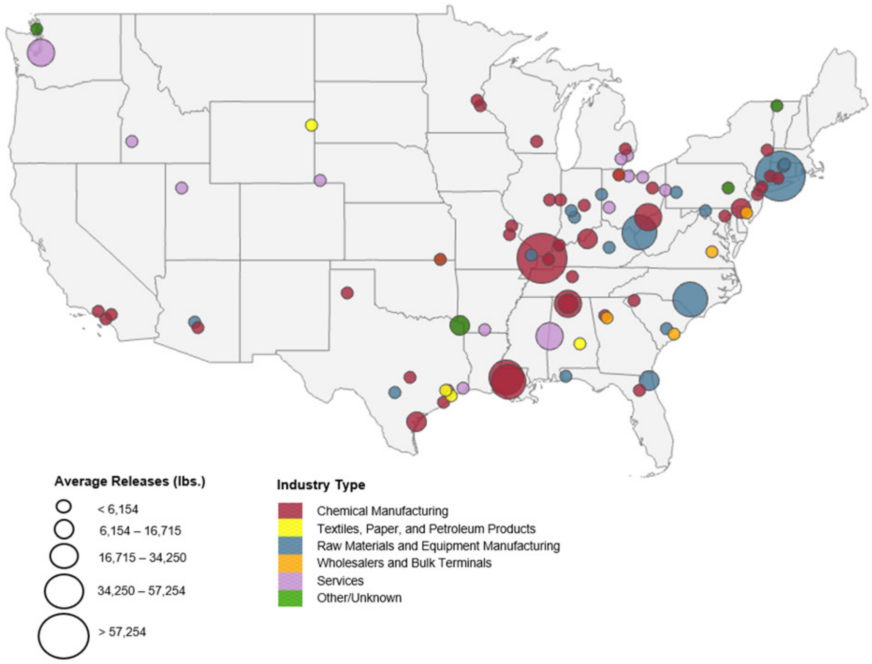


Data Source: TRI.

The facilities reporting PFAS releases had a similar spatial distribution to the PFAS-producing facilities identified in the CDR data, with a higher concentration in the eastern half of the continental United States and a few facilities spread throughout the central and western parts of the country (**Figure 4-17**). The average yearly release volume in pounds is indicated by marker size and the facility's NAICS code groupings are shown using various colors. The TRI sectors are fairly evenly spread out across the reporting facilities, with the exception of Wholesalers and

Bulk Services, which is predominantly seen in the eastern range from Southern Carolina to New Jersey. United States Enrichment Corp Paducah Gaseous Diffusion Plant in Kevil, Kentucky had the largest average reported PFAS release at 120,450 pounds, with the second largest at 94,551 pounds by Covidien LP in North Haven, Connecticut. The PFAS-producing facility with the largest average reported release was Honeywell International Inc – Baton Rouge Plant in Louisiana, with an average reported production volume of 38,901,329 pounds and an average reported release of 57,254 pounds (0.15%).

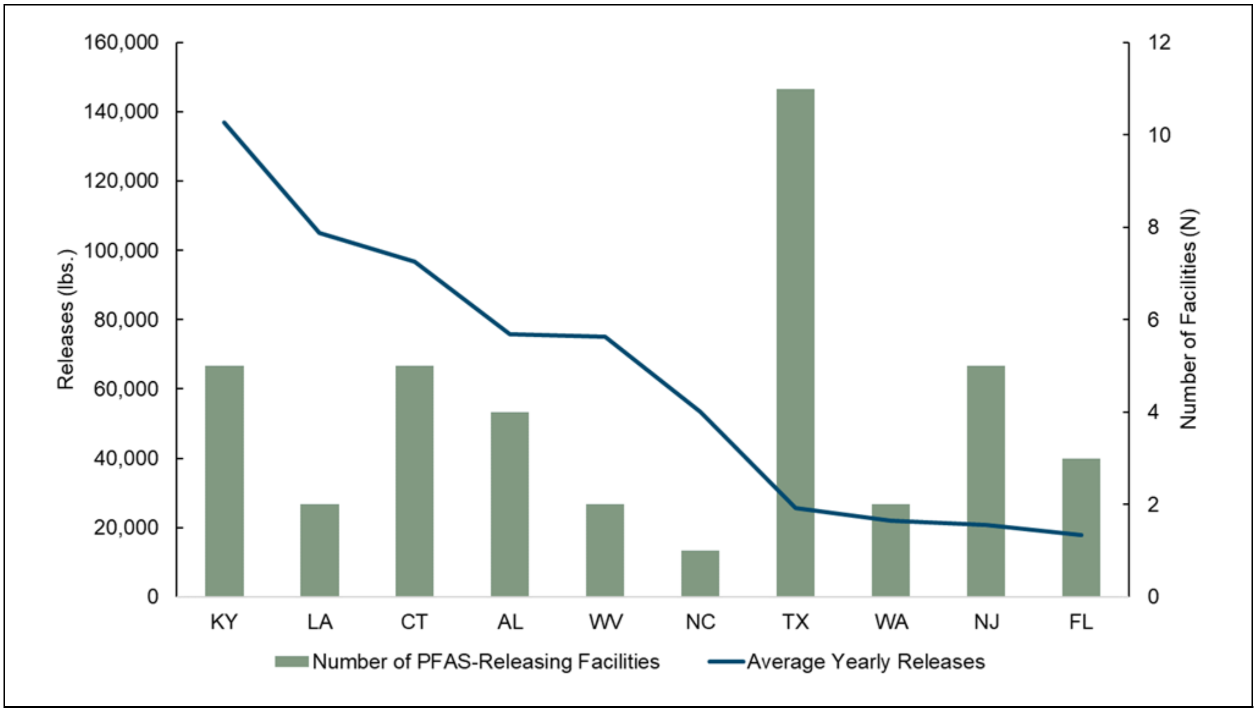
Figure 4-17. Spatial Distribution of Onsite Releases by Industry Sector (2012–2021)



Data Source: TRI.

At the state level, Kentucky had the largest average yearly PFAS release with 136,997 pounds, followed by Louisiana with 105,097 pounds, and Connecticut with 96,676 pounds (**Figure 4-18**). These three states alone accounted for over 50% of the total reported volume of PFAS releases across the United States. The average yearly release trends differ from the states with the largest number of facilities reporting PFAS releases; Texas had the most locations reporting PFAS releases with 11 facilities, Ohio had the next highest with eight facilities reporting releases, and Kentucky, Connecticut, and New Jersey all had five facilities reporting releases. The difference seen in these trends is a result of a few facilities reporting very large releases in Kentucky and Louisiana compared to the average yearly PFAS release across all states of 23,632 pounds.

Figure 4-18. TRI-Reported PFAS Releases and Number of Reporting Facilities by State (2012–2021)



Data Source: TRI.

4.2.5 PFAS Trends

We examined two sources of PFAS supply (CDR and BEA) and one source of demand trends (BEA) to assess how PFAS risk in the United States is changing over time. The trends we observed indicate stable to declining annual production volumes of PFAS in the economy at approximately 3 billion pounds per year. The data we evaluated suggest that the United States faces steadily accumulating risk of PFAS exposure. The national PFAS manufacturing and importing volumes reported in the CDR data provide a wide but largely steady-to-declining range of possible PFAS production volumes for the United States. Though economic data on national production from BEA are limited in their ability to isolate PFAS production and consumption, our nearest proxies for them also suggest steady-to-declining new PFAS volumes in the country.

We established a trendline for chemicals sector output by dividing the dollar value of chemical commodity output from the chemicals sector (BEA, 2023) by its corresponding producer price index (United States Bureau of Labor Statistics, 2023). Dividing by the producer price index controls for changes in the cost of production that may cause physical and economic output trends to diverge. Our proxy index for PFAS supply, the United States chemicals sector (NAICS 325), has shown steady-to-declining output and has comprised a declining share of total economic output over the past decade.

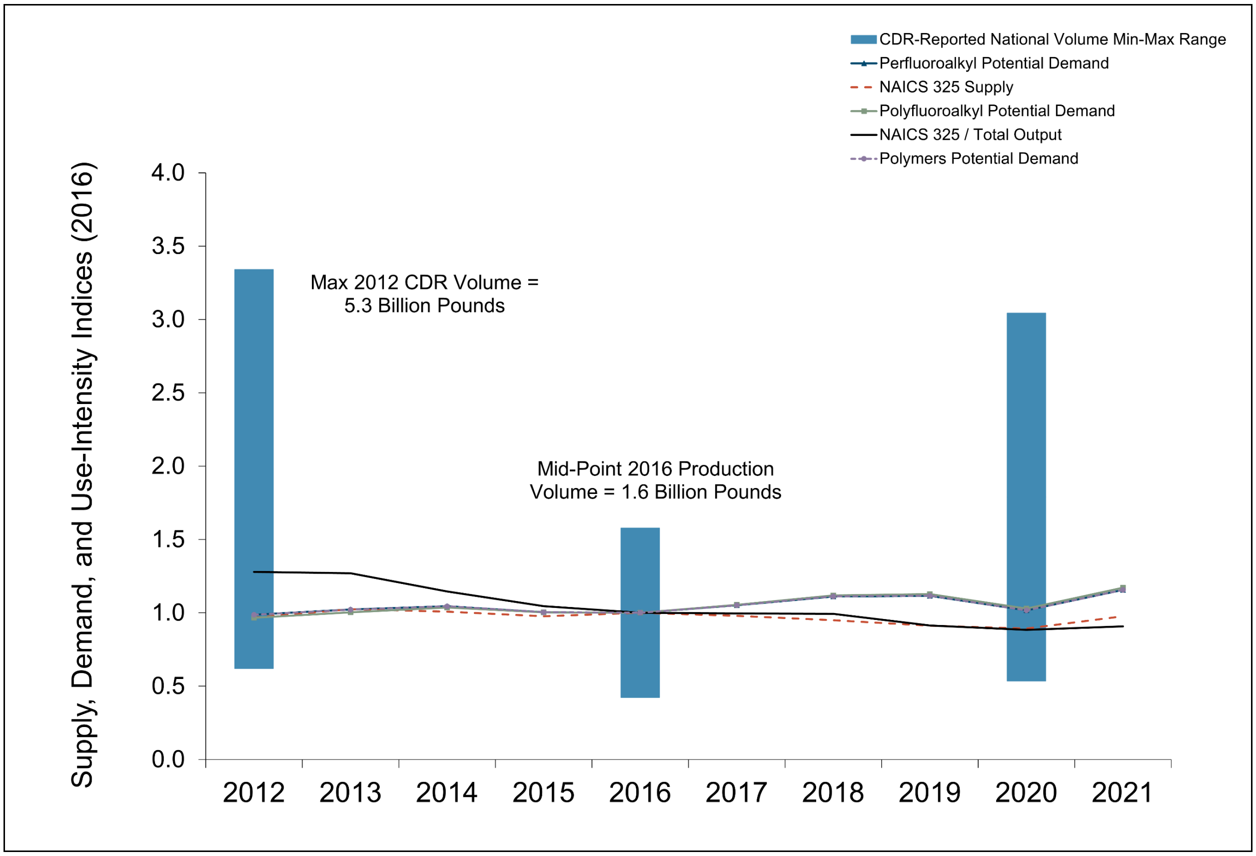
This decline in the intensity of PFAS use in the economy is offset by a modest rise in the output of sectors that are potential sources of PFAS demand. We established a proxy for PFAS demand by category by constructing a demand index based on the output of sectors purchasing from PFAS-producing sectors. This demand index has risen an average of 16% since 2016 with little variation across PFAS categories. This rise in the output of PFAS-producing sectors is offset by a declining intensity of chemicals sector (our proxy for PFAS production) use by these sectors, which has declined steadily since 2012.

The decline in use intensity combined with the steady production volumes over the past decade suggest that PFAS production may not be coupled with overall economic growth. Moreover, the modest trade in PFAS products outside of polymers suggest that growth in foreign markets may not drive larger domestic PFAS production either. Absent policy intervention or novel applications for PFAS, steady-to-declining United States production of PFAS may persist regardless of domestic or global economic growth projections, which are currently approximately 1%–2% for advanced economies in the coming years (International Monetary Fund, 2023). These steady trends in PFAS production are concerning given the risk of PFAS exposure in products, annual release rates of 0.01%–0.02%, and environmental accumulation risks due to long chemical half-lives.

> PFAS production has been steady in the United States. This trend is concerning given the risks of PFAS exposure in products and releases into the environment.

Figure 4-19 presents the trends in supply, demand, and use intensity. The figure presents 2016 as a benchmark year (i.e., equal to one) for all trends. The green bars present the range of CDR-reported national volumes relative to the midpoint of 2016 reported values, which were 1.6 billion pounds as noted in the figure. The width of the min-max ranges in the CDR-reported data makes it hard to assess PFAS output trends. The indices we constructed to proxy for supply and demand in the PFAS commodity market are relatively steady against the movement in the ranges from the CDR data. The CDR data for 2016, while generally the most complete in terms of reporting, show the narrowest range and significantly lower total volumes, whereas 2012 and 2020 show consistent ranges with slightly declining volumes, more consistent with the supply and demand indices.

Figure 4-19. Indices of Supply, Demand, and Use Intensity with Production Volume Ranges for PFAS



4.2.6 Data Gaps, Limitations, and Uncertainties

Production Volumes. The number of distinct PFAS make accounting for their production and use challenging. While we observed as much as 3.2 billion pounds of annual PFAS production in the reported chemicals, we did not identify data sources for the production volumes associated with the others. The unreported PFAS production volumes could be relatively small, comparable, or much greater than the CDR-reported national production volumes, with a range of 1.6–3.2 billion pounds per year over 2012, 2016, and 2020 at their midpoint with wide ranges due largely to facility-level data being heavily classified as CBI. CBI data claims vary by year even at the facility level (e.g., Honeywell International reported 80,000,000 pounds of a certain PFAS chemistry in 2016 that was classified as CBI in 2020). This variability limits the comparability of CDR data across years.

Industry Sectors. It is helpful to identify which sectors of the economy produce and consume PFAS to assess production trends in the context of economic conditions. However, developing an economic characterization of PFAS manufacturing is challenged by the fact that many facilities identify under multiple NAICS codes, each of which could represent either their production of PFAS or other chemicals. When facilities identify their sector, they do so with 6-digit specificity, but it is most accurate to categorize PFAS production as occurring predominantly within the broader, 3-digit chemicals sector (i.e., NAICS 325). PFAS production is a small fraction of total chemicals sector output, meaning relatively large variation in PFAS production could occur without much apparent change in overall chemicals production. Many facilities do not report a NAICS code; and available NAICS association data from other sources also offer multiple codes and are not prioritized for PFAS production. Our NAICS code distribution of PFAS production is necessarily based on facility-level reporting but facility-level data represented approximately 10% of national production volumes, which may not reflect the actual NAICS distribution of national production.

Supply and Demand. Proxy measures for PFAS supply and demand are coarse approximations of actual PFAS manufacturing activity. The construction of our demand index assumes that the pattern of demand for PFAS is like that of the industries that produce it. Particularly given that PFAS production is small relative to the total output from PFAS-producing sectors, the actual sectoral distribution of PFAS demand could differ markedly while remaining consistent with the aggregate distribution of chemicals demand.

Trade. Our identification of PFAS in trade data is limited. The lack of trade activity in perfluoroalkyl substances and polyfluoroalkyl substances may partly reflect a lack of coverage for their chemistries. HS codes are updated based on changes in trade patterns and/or technological developments. A single HS code is not designated for use of the entire universe of PFAS, or the categories used throughout these analyses—perfluoroalkyl substances, polyfluoroalkyl substances, and polymers. HS codes vary in specificity, some only include a single chemical, while others include a whole class of chemicals. There are also HS codes that capture “miscellaneous” chemicals and “other” chemicals that are not well-defined by other codes available; therefore, we could not capture all imports and exports of PFAS. It is also possible based on the HS code descriptions that chemicals that are not PFAS were included and/or PFAS were redefined.

Environmental Releases. There are several important aspects of PFAS risk that we have not attempted to capture. We only assessed releases reported to the U.S. EPA under TRI, which does not include PFAS releases that impact certain populations, such as at military bases. We also did not attempt to capture waste discharges, although some of the TRI facilities covered in the PFAS releases section are waste treatment sites.

Focus on PFAS Productions. We are not attempting to filter to consumer products, rather we are characterizing the overall PFAS commodity market, only part of which supplies consumer products. We were not able to identify a comprehensive compilation of the PFAS concentrations in consumer goods and respective trends in domestic supply and demand.

4.3 PFAS Regulatory Trends and Alternatives

Select regulations focused on reduction or restriction of PFAS use in consumer products or overall use are highlighted in **Figure 4-20**. Regulations were selected based on international policies that the United States could adopt (e.g., becoming a ratifying party of global treaties), as well as influential state-level policies.

The following sections will further detail these key regulations, in addition to overviewing other adopted and proposed PFAS regulations at the international, federal, state, and local levels and available alternatives that manufacturers may shift to because of regulations. Overall, much of the regulations are general or refer to PFAS as a class. However, among the regulations that specify individual PFAS, 30 were identified with the majority classified as perfluoroalkyl substances. Additional information on the regulations is included in the database (*PFAS Regulation Index.xlsx*).

4.3.1 Regulatory Trends

Select International Regulations

The Stockholm Convention and the European Union. With increasing scientific evidence of the exposure pathways and environmental and human health effects, countries have increasingly proposed standards and restrictions on PFAS. Countries that are member states of the European Union have primarily addressed PFAS through EU regulations and as ratifying parties of the Stockholm Convention.[7]

The United States observes meetings and technical working groups of the Stockholm Convention but has yet to be a ratifying party; however, there are over 100 countries that are ratifying parties (Stockholm Convention, n.d.-a). As early as 2009, the Stockholm Convention on Persistent Organic Pollutants listed the production and use of PFOS, its salts, and perfluorooctanesulfonyl fluoride (PFOSF [precursor to PFOS]) to be phased out of use when alternatives were available, with the goal to eliminate their production and use (Stockholm Convention, 2010). The Convention permitted exemptions until 2020 (OECD, 2023). Subsequently, PFOA and PFHxS (along with their salts and related compounds) were added in 2019 and 2022, respectively. Currently, the Persistent Organic Pollutants Review Committee is reviewing a proposal from Canada to consider long-chain PFCAs.

The Rotterdam Convention and the European Union. An additional global treaty taking action to reduce or eliminate PFAS is the Rotterdam Convention, which addresses industrial chemicals and pesticides; ratifying parties seek to promote shared responsibility and cooperative efforts in the international trade of hazardous chemicals and contribute to the environmentally sound use of those hazardous chemicals. The Rotterdam Convention develops a list of chemicals called Annex III, which includes any industrial chemicals and pesticides that were banned or severely restricted by at least two parties and that the Conference of Parties have subjected to the Prior Informed Consent procedure. Ultimately, the list ensures that chemicals are not exported to countries that have bans or restrictions in place. So far, only PFOA and PFOS (and their salts and related compounds) are included in Annex III. As with the Stockholm Convention, the United States observes meetings and technical working groups but is not a ratifying party (Office of Environmental Quality, n.d.).

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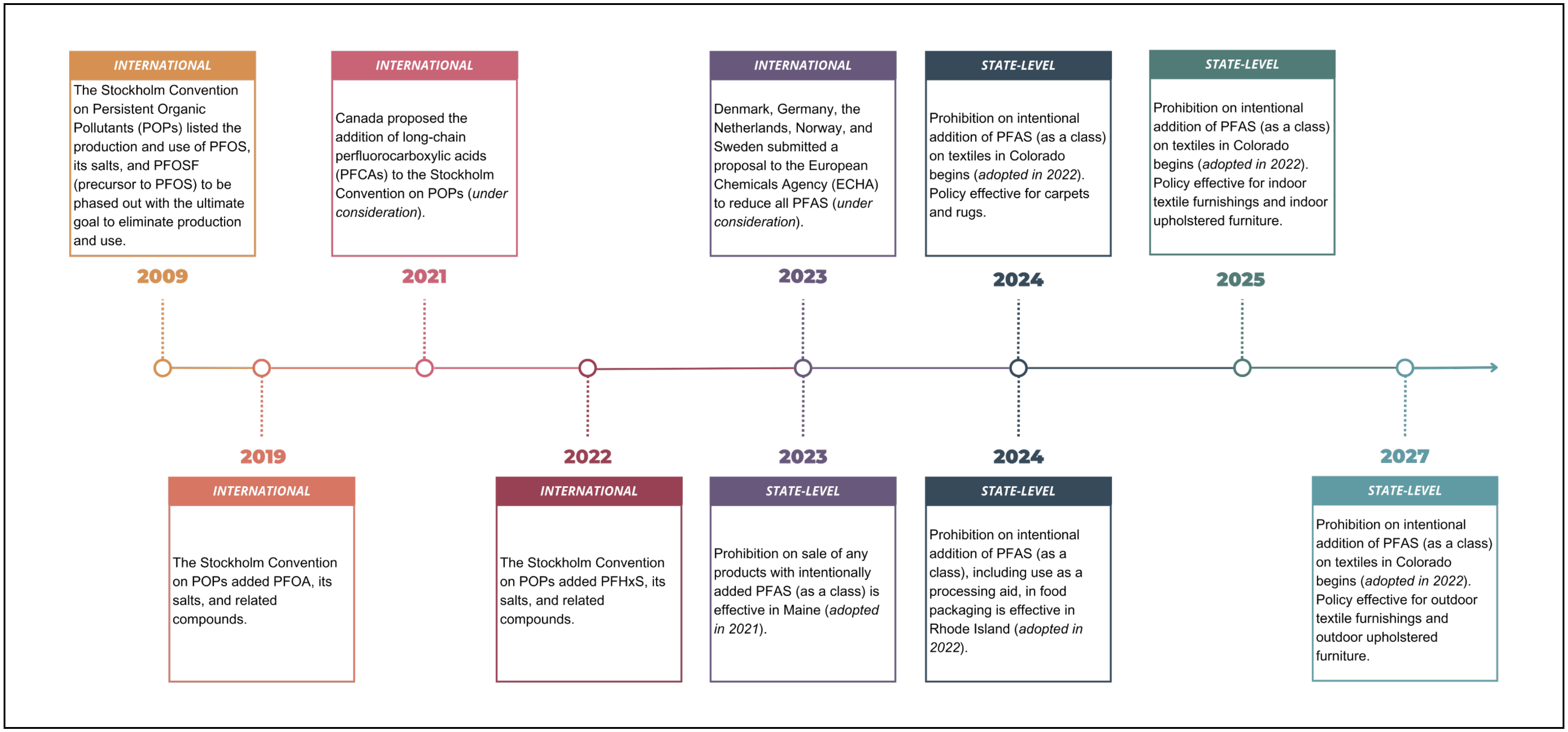
[7] The Stockholm Convention on Persistent Organic Pollutants "is a global treaty to protect human health and the environment from chemicals that remain intact in the environment for long periods, become widely distributed geographically, accumulate in the fatty tissue of humans and wildlife, and have harmful impacts on human health or on the environment" (Stockholm Convention, n.d.-b).

Figure 4-20. Select Regulations on Reducing and Restricting PFAS



2009

INTERNATIONAL

The Stockholm Convention on Persistent Organic Pollutants (POPs) listed the production and use of PFOS, its salts, and PFOSF (precursor to PFOS) to be phased out with the ultimate goal to eliminate production and use.

2019

INTERNATIONAL

The Stockholm Convention on POPs added PFOA, its salts, and related compounds.

2021

INTERNATIONAL

Canada proposed the addition of long-chain perfluorocarboxylic acids (PFCAs) to the Stockholm Convention on POPs (*under consideration*).

2022

INTERNATIONAL

The Stockholm Convention on POPs added PFHxS, its salts, and related compounds.

2023

INTERNATIONAL

Denmark, Germany, the Netherlands, Norway, and Sweden submitted a proposal to the European Chemicals Agency (ECHA) to reduce all PFAS (*under consideration*).

2023

STATE-LEVEL

Prohibition on sale of any products with intentionally added PFAS (as a class) is effective in Maine (*adopted in 2021*).

2024

STATE-LEVEL

Prohibition on intentional addition of PFAS (as a class) on textiles in Colorado begins (*adopted in 2022*). Policy effective for carpets and rugs.

2024

STATE-LEVEL

Prohibition on intentional addition of PFAS (as a class), including use as a processing aid, in food packaging is effective in Rhode Island (*adopted in 2022*).

2025

STATE-LEVEL

Prohibition on intentional addition of PFAS (as a class) on textiles in Colorado begins (*adopted in 2022*). Policy effective for indoor textile furnishings and indoor upholstered furniture.

2027

STATE-LEVEL

Prohibition on intentional addition of PFAS (as a class) on textiles in Colorado begins (*adopted in 2022*). Policy effective for outdoor textile furnishings and outdoor upholstered furniture.

KEY POINTS

- Federal and international regulations as of May 2023 target a few individual PFAS, whereas state regulations largely refer to bans on "per- and polyfluoroalkyl substances" for production of or use in specific products.
- Several states (CA, CO, CT, HI, IN, ME, MD, MN, NY, OR, RI, VT, WA) adopted current policies aiming to prohibit PFAS from certain consumer products, with food packaging being among the most common prohibitions.
- PFAS are known to provide high performance for their desired uses (e.g., achieves water or stain repellence) at very low concentrations for a low cost, which has driven adoption and proliferation across several industries.
- Some industries are shifting to removing PFAS as a class rather than substituting for less-studied and regulated PFAS.
- The large class of PFAS presents challenges for regulatory bodies and industries. Regulatory bodies are challenged with restricting PFAS use as a class or one-by-one, in addition to continually learning applications for PFAS in consumer products. Industries are often challenged with complying with the spectrum of PFAS restrictions that vary across states.
- In some applications, PFAS can be readily substituted with minimal impact on actual or perceived performance, whereas other applications are less easily replaced due to the importance of the PFAS' performance to meet product expectations.
- The primary chemistries seen emerging on the market as potential substitutes for PFAS include silicones and siloxanes, anionic surfactants, nonionic surfactants, branched polymers, and hydrocarbon-based solutions.

Five countries have proposed to restrict around 10,000 PFAS across the European Union. The proposal is currently under consideration with the ECHA.

The European Food Safety Authority. As for additional action by member states of the EU, in September 2020, the European Food Safety Authority (EFSA) established a new tolerable weekly intake (TWI) of 4.4 ng/kg body weight per week for the sum of PFOA, PFOS, PFNA, and PFHxS (additional details are provided in **Section 4.4.4**) (EFSA Panel on Contaminants in the Food Chain, 2020). However, significant chemical restrictions for member states of the EU fall under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), which the EU adopted to 1) improve the protection of human health and the environment from the risks that can be posed by chemicals, 2) enhance the competitiveness of the chemicals industry, and 3) promote alternative methods for the hazard assessment of substances to reduce animal testing (ECHA, n.d.). REACH regulation includes a Candidate List of Substances of Very High Concern (SVHCs), which places legal obligations on importers, producers, and suppliers of the substances. Several PFAS are on the list, including PFOA, PFOS, PFHxS, PFHpA, and GenX chemicals. Similar to the Stockholm and Rotterdam Conventions, PFAS have been added to the list one-by-one. However, in January 2023, five countries (Denmark, Germany, the Netherlands, Norway, and Sweden) submitted a wide-ranging proposal to the ECHA. The proposal "aims to reduce PFAS emissions into the environment and make products and processes safer for people" (ECHA, 2023). Under the definition reported in the proposal, over 10,000 PFAS would be addressed. As of March 2023, the proposal will undergo a 6-month open consultation, followed by ECHA committees' evaluation. Sweden's involvement in the proposal to ECHA was driven by the Swedish Chemicals Agency's objective for a "non-toxic environment" by 2030, which includes reduction of exposure to PFAS (Swedish Chemicals Agency, 2023). Similarly, Denmark has also been actively reducing its exposure to PFAS and as of July 2020, the use of PFAS in cardboard and paper FCMs in the country is prohibited.

Australia and Canada. Outside of the EU, countries like Australia and Canada have taken additional steps toward restricting PFAS and its contamination in the environment. Australia has developed a PFAS National Environmental Management Plan and other frameworks to ensure consistent management, as well as the Australian Industrial Chemicals Introduction Scheme, which requires importers and manufacturers to provide information on any existing or new PFAS in use in Australia (OECD, n.d.-c; Australian Government PFAS Taskforce, 2019). Australian Industrial Chemicals Introduction Scheme also places export and import controls on PFOS and select PFOS-precursors. In addition to its proposal to the Persistent Organic Pollutants Review Committee, starting in 2006, Canada initiated environmental monitoring for PFAS, issued guidelines for PFOA and/or PFOS in drinking water, groundwater, soil, and wildlife, and published regulations on manufacture, use, sale, and import. The latter actions began with PFOS (2008) and expanded to PFOA and long-chain PFCAs (2016). In 2022, the proposed “Prohibition of Certain Toxic Substances Regulations, 2022” would provide stricter controls on PFOS, PFOA, and long-chain PFCAs by removing or providing time limits for current exemptions. Additionally, Canada plans to publish a state of PFAS report in 2023 to address the broad class of PFAS, noting that the PFAS used to replace regulated PFOA, PFOS, and long-chain PFCAs may also be associated with environmental and/or human health effects (OECD, n.d.-d).

Asia and the Middle East. China placed a ban on the application, export, import, production, and transportation of PFOS, its salts, and PFOSF in 2014; there were only specific exemptions and acceptable uses permitted (OECD, n.d.-e). According to the International Pollutants Elimination Network in 2019, PFAS were largely unregulated in 12 Middle Eastern and Asian countries (Bangladesh, Egypt, India, Indonesia, Japan, Jordan, Lebanon, Malaysia, Nepal, Sri Lanka, Thailand, and Vietnam)—except for those that accepted the amendment listing of the Stockholm Convention, and therefore had PFOS regulation (International Pollutants Elimination Network (IPEN), 2019).

U.S. Federal Regulations

PFAS in the Environment. Despite the increasing regulations on PFAS in other countries, especially member states of the EU, the United States does not have any federally enforceable standards or regulations for PFAS in the environment. However, in October 2021, the U.S. EPA announced a PFAS Strategic Roadmap for 2021 to 2024. The roadmap overviewed key actions across the Agency that would facilitate research, restriction, and remediation of PFAS (U.S. EPA, 2021c). Key actions included using enforcement tools such as the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and Safe Drinking Water Act (SDWA). As of August 2022, the U.S. EPA announced a proposal to designate PFOA and PFOS as hazardous substances under CERCLA, which would require releases of PFOA and PFOS to be reported and facilitate cleanup of contaminated sites (U.S. EPA, 2022g). In March 2023, the U.S. EPA announced a significant proposal to establish the first-ever national drinking water standard to limit six PFAS—PFOA, PFOS, PFNA, HFPO-DA, PFHxS, and PFBS—under SDWA; the regulation is scheduled for finalization in 2023. In addition to requiring the reduction of the six PFAS in drinking water, public water systems will also be required to monitor for the six PFAS and notify the public of the results (U.S. EPA, 2023b). Aside from those proposals, there has yet to be additional federally enforceable action on PFAS.

PFAS in Consumer Products. The U.S. FDA announced a voluntary phase-out of PFAS in food contact substances (e.g., food packaging). The voluntary phase-out began in January 2021 with a focus on one PFAS: 6:2 FTOH. The three manufacturers that committed to the voluntary phase-out planned for 3 years to phase out their use of 6:2 FTOH and an additional year and a half to exhaust existing stock (Hahn & Mayne, 2020). Additionally, similar to the EFSA, the FDA also requires scientific review of food contact substances prior to authorization to enter the market. FDA authorized PFAS usage as a coating to make cookware nonstick, resin in forming certain parts of food processing equipment, processing aids, and greaseproof agents in paper and paperboard food packaging. Whereas short-chain PFAS, such as 6:2 FTOH, are only under a voluntary phase-out, FDA revoked authorization to use long-chain PFAS in food packaging effective as of November 2016 (U.S. Food & Drug Administration, 2022c).

Notably, three other proposals regarding consumer products are under federal consideration as of 2023. The “PFAS Free Military Purchasing Act” was introduced in 2021 to prohibit the U.S. Department of Defense from the procurement and purchase of any “covered item” containing PFAS; however, further actions have not been taken. Items covered by the act included nonstick cookware or food service ware; food packaging materials; furniture or floor waxes; carpeting, rugs, curtains, or upholstered furniture; personal care items; dental floss or toothpaste; sunscreen; umbrellas, luggage, or bags; ski wax; car wax and car window treatments; cleaning products; and shoes and clothing for which treatment with PFAS was not necessary for an essential function. The “No PFAS in Cosmetics Act” was introduced in June 2021 and the “Keep Food Containers Safe From PFAS Act of 2021” was introduced in November 2021, but neither bill has yet to move forward throughout the legislative process. The bills are intended to prohibit the intentional addition of PFAS considered as a class in cosmetics or food packaging (H.R.6026 2021; S.2047, 2022).

U.S. State Regulations

In the absence of regulations at the federal level, several states have adopted and/or proposed regulations on PFAS-containing products. In addition to regulations on PFAS-containing products, PFAS policies at the state level include those ranging from drinking water monitoring, firefighting foam take-back programs, and impacts on leachate from landfills to research and development to further address PFAS contamination and remediation. **Figure 4-21** displays the states with adopted or proposed policies related to PFAS as of May 2023.

Twenty-four states have adopted PFAS policies, and an additional 12 states have proposed PFAS policies introduced in their state legislatures as of May 2023. Based on our search, 16 states have not adopted or introduced any PFAS policies as of May 2023. Current policies primarily focus on the outdoor environment: cleanup and remediation of contaminated PFAS sites, maximum contaminant levels and monitoring for drinking water, research funding on landfill leaches, and so on. Additional details on these policies are included in the database (*PFAS Regulation Index.xlsx).*

Regarding policies on PFAS-containing products, 13 states have adopted policies and an additional 13 states have proposed policies (shown in **Figure 4-22**).

Figure 4-21. Adopted or Proposed State-Level PFAS Policies

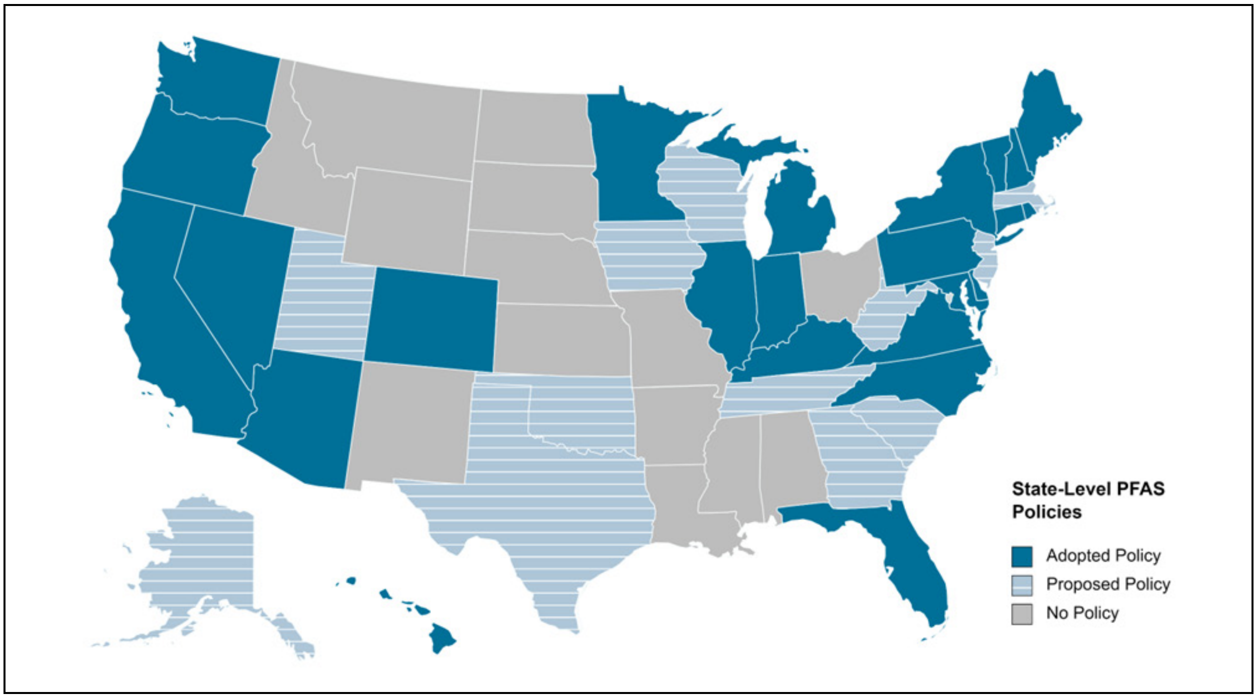
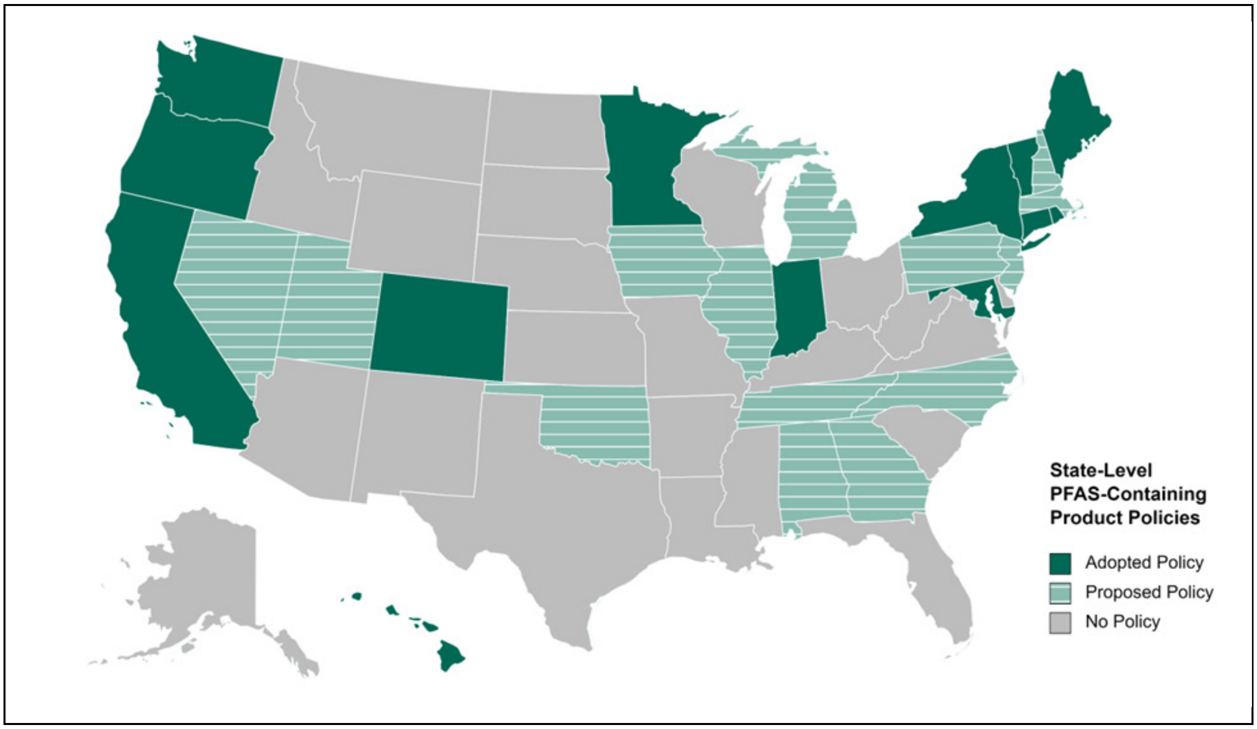


Figure 4-22. Adopted or Proposed State-Level PFAS Policies on Consumer Products Specifically



Among adopted or proposed state policies specifically on PFAS-containing products, regulations largely either 1) involved the prohibition of the manufacture, distribution, and sale of certain products or 2) required disclosure or reporting of PFAS intentionally added to the products. With the exception of AFFFs within the "Miscellaneous Household or Industrial Products" category, most policies focus on containers and packaging (e.g., food packaging), carpets and rugs, fabric treatments, and general children's products. Additional details on these policies are included in the database (*PFAS Regulation Index.xlsx)*.

Notably, several regulations regarding the prohibition of PFAS in products only apply "if (safer) alternatives are available," without specifying what qualifies as "safer." Furthermore, several regulations only apply if PFAS in products is an "unavoidable use." The language in these regulations is significant because PFAS can still be present in products for several reasons:

- PFAS are byproducts and/or contaminants throughout the manufacture and distribution process (as discussed in **Section 4.1.2**),
- There are no "safer" alternatives available, and
- PFAS use is "unavoidable."

Additionally, across states, there are different interpretations of what constitutes "intentionally added" PFAS and presence of PFAS. As an example, Hawaii's adopted bill prohibiting food packaging that contains PFAS defined "intentionally introduced" to mean "deliberately utilized PFAS in the formulation of a package or packaging component where the continued presence of the PFAS is desired in the final package or packaging component to provide a specific characteristic, appearance, or quality" (H.B. No. 1644, 2022). Conversely, Colorado's adopted bill prohibiting several consumer products that contain PFAS defined "intentionally added PFAS chemicals" to include the PFAS that a manufacturer intentionally added to the product that has a functional or technical effect on the product, as well as the "PFAS chemicals that are intentional breakdown products of an added chemical" (H.B. 22-1345, 2022). Both definitions, that used by Hawaii and that used by Colorado, are used by other states. One industry expert stated that the varying interpretations of "intentionally added" can significantly affect industries (Name withheld, 2023e).

Furthermore, across state regulations, there are different interpretations of what constitutes the "presence" of PFAS. California's policy on juvenile products has a specific definition where the presence of PFAS was defined at or above 100 parts per million, as measured in TOF, in the product or product component (A.B. 652, 2021). Although 13 states are at the forefront of policies reducing or eliminating PFAS-containing products from manufacture, distribution, and sale, the differences in (or lack of) definitions lead to varying compliance and understanding by manufacturers and suppliers of the products.

SUSTAINABLE PACKAGING INDUSTRY VETERAN

Key Point: Companies are working through challenges to phase out PFAS as a processing aid to comply with increasing regulations.

- Regulations across the country are restricting the use of PFAS as a processing aid, especially for manufacturing food packaging. The definitions of “intentionally added” vary by state, where processing aids are considered under “intentionally added” for some states but not others. Companies attempt to adhere to the stricter regulations by discontinuing the use of PFAS, such as the regulation in Rhode Island in which PFAS as a processing aid is not exempt.
- There are efforts in the industry to find alternative processing aids, but viable alternatives cannot currently meet the demands of the entire plastic industry.
- The challenges that the industry is facing in eliminating PFAS are centered on manufacturing capability and efficiency, as well as product quality. An example is paper-based food service ware; currently, there is no other existing compound that acts as an appropriate barrier for paper like PFAS, which makes it difficult to replace.
- There are few, if any, government-adjacent groups or regulatory bodies working with companies to find alternative processing aids. Companies largely work with their suppliers to find alternatives.

Bans on Consumer Products

Containers and Packaging. Food packaging is one consumer product that has been at the forefront of state-level legislation. As of May 2023, 20 states (CA, CO, CT, HI, IL, IA, ME, MD, MA, MI, MN, NV, NH, NY, NC, OR, PA, RI, VT, and WA) have adopted or proposed policies to prohibit the manufacture, sale, and distribution of food packaging or food service ware that contains PFAS. The bans are under two categories: 1) ban on only paper- or plant-based food packaging material or 2) ban on all food packaging material regardless of material. Among the 20 states, most bans are on the full class of PFAS, which was typically defined as “a class of fluorinated organic chemicals containing at least one fully fluorinated carbon atom” in the legislation. The only variations in the definition across states were in reference to the class: “a class,” “all members of the class,” and “any member of the class.” The remaining states use “perfluoroalkyl and polyfluoroalkyl substances” and “PFAS” broadly without a definition.

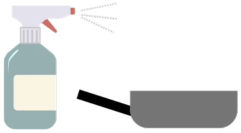
SUSTAINABLE PACKAGING INDUSTRY VETERAN

The lack of concise technical rules and standard definitions, as well as short timeframes are preventing the industry from finding safe and scalable PFAS alternatives. There are several states with PFAS bans in packaging, but they are not consistent, which makes compliance difficult.

Nine of the states (CA, CT, IA, MD, MN, NH, NJ, RI, and WA) prohibiting PFAS-containing food packaging are also Toxics in Packaging Clearinghouse members. The Toxics in Packaging Clearinghouse jointly developed the Model Toxics in Packaging Legislation to reduce cadmium, hexavalent chromium, lead, and mercury in packaging and packaging components sold and/or distributed in the United States. The legislation has since been adopted by 19 states; most recently, the legislation has been proposed to include PFAS (in addition to other chemicals of concern) (Toxics in Packaging Clearinghouse, 2022). Although concentration limits were placed on four metals related to the legislation, the current proposal prohibits any detectable PFAS in any package or packaging component.

Cosmetics and Personal Care Products. California, Colorado, and Maryland have passed policies to prohibit PFAS in cosmetic products. Effective at the start of 2025, cosmetic products (defined as articles applied to the human body and intended for beautifying, cleansing, promoting attractiveness, or altering the appearance) containing intentionally added PFAS (considered as a class) may not be manufactured, sold, delivering, held, or offered for sale in California and Colorado (H.B. 22-1345, 2022; A.B. 2771, 2022). Notably, rather than citing the class of PFAS, Maryland specified 13 specific PFAS that were prohibited in cosmetic products. The 13 chemicals included PFOA, PFOS, PFNA, and their salts (i.e., potassium perfluorooctanesulfonate [CASRN 2795-39-3] and sodium nonadecafluorodecanoate [CASRN 3830-45-3]) (H.B. 643, 2021).

Additionally, 12 other states have proposed policies in their state legislatures regarding the ban of PFAS. Among policies on cosmetic and personal care products, four states (CA, GA, NY, and VT) have proposed PFAS bans on menstrual (also known as feminine hygiene) products. In April 2023, the Vermont Senate passed a bill to prohibit the class of PFAS in cosmetic and menstrual products. As of May 2023, the bill was read to the Vermont House of Representatives. The bill specified that cosmetic or menstrual products with a “technically unavoidable trace quantity of a chemical or chemical class listed” would not be in violation if the trace quantity was a result of 1) natural or synthetic ingredients, 2) the manufacturing process, 3) storage, or 4) migration from packaging. Notably, the bill did not include one-year waivers for the presence of PFAS in cosmetic or menstrual products (only 1,4-dioxane and lead and lead compounds) (An act relating to regulating cosmetic and menstrual products… S.25, 2023).



Household Products. Overall, there are limited policies covering PFAS-containing household products. As of yet, states have not adopted policies to prohibit or reduce PFAS in cookware. However, several states, including Massachusetts, Minnesota, New York, Rhode Island, and Vermont, have proposed policies to do so. Across the states, definitions of “cookware” have minute differences—although some states specify use in homes *and* restaurants, others only specify use in homes (H.2197, 2023; S.F. 834, 2023; S.B. 76, 2023; A3556A, 2023). Other policies include cleaning products or fabric treatments but have not been adopted.

Unique policies in New York have targeted anti-fogging sprays and wipes (proposed 2022) and architectural paints (proposed 2023), both of which cover the class of PFAS (A3563A, 2023; A3556A, 2023).

State-level policies are primarily focused on PFAS in food packaging or food service ware and textiles. Policies target the class of PFAS, and regulatory bodies have acknowledged that more time is needed to identify suitable PFAS substitutions in certain consumer products, such as outdoor apparel for severe wet conditions.

Outdoors, Outdoor Recreation, Sports, and Fitness. Ski wax has been one of the main consumer products of the "Outdoors, Outdoor Recreation, Sports, and Fitness" category to be included in policies. As discussed previously (**Section 4.1.1**), fluorocarbon-based waxes were banned by the International Ski Federation with other ski and snowboard associations and federations following suit. Though the ban was intended to start in the 2020–2021 winter season, it was postponed to the 2023–2024 season as the federation continues to refine their procedures and testing devices. Thus far, Minnesota, New York, and Vermont have policies posed to ban the class of PFAS in ski wax. Vermont was the first state to effectively prohibit the class of PFAS in ski wax as defined as "a lubricant applied to the bottom of snow runners, including skis and snowboards, to improve their grip or glide properties" (S.20, 2021). Minnesota and New York both have proposed policies, but they have not been passed by both the House and Senate.

The other consumer product subject to bans in this category is artificial grass or turf. State policies on artificial turf have been introduced in Connecticut, Massachusetts, and Vermont.

Textiles, Clothing, Apparel, Jewelry, and Accessories; Furniture, Furnishings, and Décor. Alongside food packaging, textiles are the focus of several state-level legislations on consumer products. Seventeen states have policies on textiles: eight states have adopted policies (CA, CO, ME, MD, MI, NV, NY, and VT, and nine have proposed policies (IL, MA, MN, NV, NH, NJ, NY, RI, and VT). Specified textiles include both wearable (e.g., indoor apparel, outdoor apparel, outdoor apparel for severe wet conditions) and non-wearable textiles (e.g., carpets, rugs, textile furnishings). In specifying certain wearable or non-wearable textiles, Colorado and other states have adopted policies in which the bans on the class of PFAS have staggered effective dates. For instance, effective dates for Colorado span from 2024 to 2027 as summarized below (H.B. 22-1345, 2022):

- January 1, 2024: Prohibited in carpets or rugs, fabric treatments, food packaging, juvenile products, and oil and gas products.
- January 1, 2025: Prohibited in cosmetics, indoor textile furnishings, and indoor upholstered furniture.
- January 1, 2027: Prohibited in outdoor textile furnishings and outdoor upholstered furniture.

These staggered effective dates provide suppliers, manufacturers, and distributors opportunities to determine suitable replacements for PFAS. Policies that have adopted staggered effective dates align with reports from industry experts that PFAS substitution in certain consumer products are harder than others, including protective garments and repellent coatings (for stain- and water resistance) (Name withheld, 2023d; Name withheld, 2023e; Name withheld, 2023e).

APPLICATION #3

General Product

- According to the adopted California policy, a new durable water-resistant jacket containing PFAS would require legible and easily discernable disclosure with the statement "Made with PFAS chemicals" starting January 1, 2025.
- The jacket would be later be prohibited from distribution and sale starting January 1, 2028.
- However, if other states adopt policies to prohibit the distribution and sale of outdoor apparel for severe wet conditions sooner than January 1, 2028, then the industry may be forced to substitute PFAS in those products sooner than 2028.

Similarly, California prohibits new textile articles (i.e., apparel, accessories, backpacks, bedding, curtains, handbags, upholstery, and others) that contain PFAS effective January 2025, but outdoor apparel for severe wet conditions has an exception until January 2028. The outdoor apparel for severe wet conditions is defined as apparel designed for outdoor sports experts, such as outerwear for offshore fishing, offshore sailing, and whitewater kayaking. Additionally, the policy establishes increasingly conservative thresholds for what constitutes the presence of PFAS in a product or product component. The thresholds, measured by TOF, are at or above the following (A.B. 1817, 2022):

- January 1, 2025: 100 parts per million (ppm)
- January 1, 2027: 50 ppm

All policies have a need for standard testing (see additional details in **Section 2.1.4**) to ensure compliance and enforcement, but this policy underscores the need for industries to have similar analytical methods and sensitivity.

Notably, apparel and other wearable textiles in many of these policies do not include personal protective equipment or professional outerwear and uniforms (A.B. 1817, 2022; A07063, 2022). However, Iowa, Maine, and Massachusetts have adopted or proposed policies to prohibit the class of PFAS in firefighting gear and personal protective equipment or to provide one-time funding to replace firefighting gear that is known to have PFAS (S.1556, 2023; HF 62, 2023; LD 206 (HP 127), 2023).

Overall, Maine has one of the most expansive policies for phasing out productions with intentionally added PFAS. In 2021, Maine passed “An Act to Stop Perfluoroalkyl and Polyfluoroalkyl Substances Pollution.” The act, effective in 2023, prohibits the sale of carpets, rugs, or fabric treatments with intentionally added PFAS, and, effective in 2030, prohibits the sale of *any products* with intentionally added PFAS “unless the use of PFAS in the product is specifically designated as a currently unavoidable use by the Department” (Maine Department of Environmental Protection, 2022).

Bans in Children’s Products. Ten states (CA, CO, IL, ME, MA, MN, NV, RI, VT, and VA) have also adopted or proposed policies to prohibit PFAS specifically in “juvenile products.” California’s policy prohibits a person, including a manufacturer, from distributing or selling juvenile products containing PFAS and requires the use of the least toxic alternative when replacing the PFAS. In alignment with the CPSC definition for “children’s products,” states define “juvenile product” to mean a product designed for use by infants and children under 12 years of age. Examples in California’s policy include baby or toddler beds and furnishings, infant carriers or seats, playmats and playpens, and strollers. Policies also state what are not included as juvenile products: electronic products, including personal computers and any associated equipment; an internal component of a juvenile product that would not come into direct contact with a child’s skin or mouth during reasonably foreseeable use and abuse of the product; and adult mattresses. California’s policy is effective in July 2023 with other states following: Colorado (effective 2024), Rhode Island (2024), and Minnesota (2025). Nevada and Vermont had immediate effect dates but only pertaining to PFOS, PFHxS, PFHpA, and PFNA. In addition to children’s products, the proposed policy in Massachusetts also calls out “child passenger restraints” (H.2197, 2023).

RETAIL PACKAGING INDUSTRY VETERAN

Key Point: The lack of unified federal regulations on PFAS poses a challenge for the industry. Industry now needs to keep up with varying state regulations.

- The industry is searching for processing aids alternatives, but it is taking time to find a suitable and safe alternative, as they do not want to fix one issue only to cause another. Alternatives need to be safe for consumers and FDA-approved, especially for products that make direct food contact.
- The misalignment of state regulations is a challenge for the industry. Finding solutions that comply with regulations across the board is extremely difficult. Regulators are putting the responsibility of eliminating PFAS on the industry, without giving an exact deadline. The government can help the industry to eliminate PFAS by having federal regulations that all states have to comply with.
- Eliminating PFAS in food packaging is difficult, particularly in packaging for products such as instant or ready-to-eat foods and food service ware. Specifically in food service ware, restaurants are not keen to switch out their large food packaging inventories.
- A PFAS-free solution for food service ware is to switch to 100% virgin materials, such as paperboard. However, there are performance tradeoffs to consider, such as lack of grease resistance.
- Industry competitors are working together to find solutions. It is important that they keep doing this, because working in silos will prevent the industry from identifying viable alternatives quickly.
- In the next 5–10 years, hopefully there will be many PFAS alternatives available, and we learn more about PFAS contamination and exposure.

Disclosure or Reporting Requirements. In addition to policies that prohibit PFAS-containing products from reaching the consumer, states have adopted and proposed policies that require chemical transparency from companies and manufacturers through disclosure or reporting requirements of PFAS. Along with prohibiting all products from containing intentionally added PFAS in Maine, there are also reporting requirements under “An Act to Stop Perfluoroalkyl and Polyfluoroalkyl Substances Pollution.” Manufacturers of all products with intentionally added PFAS are required to report PFAS presence in those products. Similarly, West Virginia requires facilities using certain PFAS to monitor and report use (effective June 8, 2023). The self-reporting of PFAS manufacture and use will require the CASRN, amount used, and any additional information required by the secretary (H.B. 3189, 2023). However, in contrast to other definitions used by states, West Virginia defined PFAS as the following: “non-polymeric perfluoroalkyl and polyfluoroalkyl substances that contain at least two fully fluorinated carbon atoms, excluding gases and volatile liquids. PFAS includes, among other substances, PFOA and PFOS.” The definition differs from those previously described because it excludes polymers (including fluoropolymers, PFPE, and side-chain fluorinated polymers). As stated in **Table 4-2** polymers comprised 19.4% of the identified PFAS used in consumer products.

As stated previously, states have not adopted policies to prohibit PFAS in cookware; however, there are policies requiring disclosure of cookware that contains intentionally added PFAS. California is the only state to adopt the policy, but six other states (MA, MN, NJ, NY, RI, and VT) have introduced the policies (A.B. 1200, 2021).

PFAS are not the only chemicals that states have adopted policies for disclosure or reporting requirements; (Safer States, n.d.) noted the success of such policies using Washington as an example. Washington requires the disclosure of more than 60 chemicals in children's products, and subsequently, retailers have developed their own policies to screen products using those chemicals and subsequently reduced purchase of those products. However, most reporting can be limited. Some states have opted for reporting of PFAS in only certain consumer products, such as cookware, or reporting of only certain PFAS (typically the legacy PFAS, such as PFOA and PFOS). This leaves a significant gap in reporting. Maine designated PFOS and its salts as a chemical of concern, and PFOS has since been elevated to a priority chemical, which requires manufacturers selling certain products containing PFOS in an amount greater than de minimis to adhere to reporting requirements (LD 2048, 2008). Manufacturers or distributors of products in the following categories are required to report: child care articles; clothing; footwear; sleepwear; toys; cookware, tableware, reusable food and beverage containers; cosmetics and personal care products; craft supplies; electronic devices; and household furniture and furnishings. Similarly, Oregon has a list of High Priority Chemicals of Concern for Children's Health because of the Toxic-Free Kids Act (2015), which only lists PFOS. However, eventually, reporters are intended to eliminate the chemicals from certain products or seek exemption (Oregon Health Authority, n.d.).

Select Local Regulations

Although a patchwork of adopted or proposed state regulations is in place, local regulations appear to be limited beyond environmental monitoring. However, there is an instance where a city issued a ban with the state following suit. In 2018, San Francisco banned single-service food service ware (e.g., cups, food wrappers, takeout containers) that contained PFAS; the ban went into effect January 2020 (Skaggs, 2018; Skaggs, 2018). Then in 2021, to go in effect January 2023, California adopted a ban on any food packaging that contained PFAS (A.B. 1200, 2021).

In contrast, rather than banning chemicals in certain products, other local regulatory bodies have banned the product as a whole. Artificial turf has been the topic of discussion across playground and sports uses; however, PFAS has not always been associated with those discussions. Artificial turf consists of turf fibers, infill (including elastomer polymers and thermoplastics; infill is commonly from recycled and shredded end-of-life tires, known as "crumb rubber"), sand and infill mixture, and backing (Zuccaro et al., 2022). The use of PFAS in plastic and rubber production can be a potential source of PFAS in artificial turf (Glüge et al., 2020). (Additional details on the use of PFAS in artificial turf is in **Section 4.1.1**). Different local regulatory bodies have placed bans on artificial turf and/or crumb rubber in favor of sustainable alternatives; however, Boston specifically called out the presence of PFAS in artificial turf. In 2022, the mayor of Boston ordered that no new artificial turf be installed in city parks citing that the city "will not be installing playing surfaces with PFAS chemicals moving forward" (Perkins, 2022).

4.3.2 Voluntary Company Phase-outs in Advance of Potential Regulations

In the United States, companies face limited pressure at the federal level to remove PFAS from their supply chains; however, multiple states have taken legislative steps toward phasing out PFAS or outright banning them in certain products. In preparation for pending state regulations, several manufacturers have voluntarily phased out PFAS from their products. For instance, with increasing evidence on the effects of PFOA on human health and the environment, PFOA was voluntarily phased out and then discontinued in the United States. The U.S. EPA cited success of the 2010/2015 PFOA Stewardship Program, in which eight major leading companies in the PFAS industry were invited to 1) achieve a 95% reduction in facility emissions to all media of PFOA (and precursors and homologues) and product content levels from 2000 to 2010, and 2) commit to working toward elimination of those chemicals from emissions and products by 2015 (U.S. EPA, n.d.-b). PFOS production has followed similar phase-outs in the United States However, as PFOA and PFOS have been phased out in the United States, often replacement compounds include alternative PFAS that have taken their place, such as short-chain PFAS like GenX chemicals and PFBS.

In addition to pending regulations, other factors contributing to manufacturers phasing out PFAS have been 1) increasing legal action against manufacturers and 2) increasing reports in both gray and peer-reviewed literature on detection of PFAS in products. Class-action lawsuits against two brands of menstrual underwear were briefly discussed in **Section 4.1.1**. Additionally, California has filed legal action against several PFAS manufacturers, including 3M, which manufactures consumer goods and products for health care, industry, and worker safety. California’s filing against 3M adds to the thousands of other legal liabilities that face the manufacturer. Since then, the company announced that it would discontinue use of PFAS across its products and exit PFAS manufacturing by the end of 2025 (3M News Center, 2022).

Furthermore, based on their report, Toxic-Free Future and environmental advocacy groups began a campaign calling upon REI Co-op to “opt out” of PFAS (Schade, 2022). More than year after the launch, REI Co-op released a statement expressing support for California’s policy to prohibit the sale, manufacture, or distribution of textile articles containing PFAS, which would affect certain apparel, backpacks, and footwear sold at REI. Additionally, REI announced it would ban PFAS in all cookware and textile products from its suppliers (Schade, 2022; REI Co-op, 2022). Some fast food chains have also announced bans on PFAS in their food packaging. PFAS Central, a project of Green Science Policy, has listed other companies and manufacturers of apparel, baby products, cosmetics and personal care products, furniture, outdoor gear, and shoes that have policies for all or select products to be “PFAS-free.”

Despite these voluntary phase-outs and patchwork of regulations, supply and demand of PFAS remains high, as shown in **Section 4.2**, especially because products that may contain PFAS and the sale of PFAS for product manufacturing remains profitable and largely unregulated.

4.3.3 PFAS Substitutes and Potential Impact on PFAS Use

Despite the functionality and usefulness of PFAS, demand is growing for alternatives that offer similar or better performance without the negative environmental and health impacts. Substitution of PFAS in new and existing products can be complicated and depends on various factors.

PFAS provide high performance in various functions at very low concentrations and at highly economical costs, which has ultimately driven adoption and proliferation across several industries. When considering potential substitutes for PFAS, product developers and formulators must consider not only the price implications of alternative chemistries, but also the regulatory landscape surrounding substitutes and how the consumer experience and performance may be impacted.

Price Factors

Fluorinated surfactants and additives are typically sold on the market at a higher price point than their non-fluorinated counterparts; however, the lower use concentrations of the PFAS-based ingredients offsets the higher price and is a more economical option for high performance across a breadth of industries and applications (Glüge et al., 2020). But individuals throughout the industry claim that fluorinated options are only typically used when non-fluorinated alternatives are not found to be fit for use or do not meet the desired performance metrics (OECD, 2022b).

Higher concentrations are required of most non-fluorinated alternatives compared to the fluorinated chemicals. The cost implications of substituting PFAS often presents a barrier to those seeking to reformulate. Ultimately, the price differential is a critical factor when it comes to evaluating the competitiveness of non-fluorinated alternatives across a variety of applications. For example, in firefighting foam applications, non-fluorinated alternatives were consistently 5%–10% more expensive to achieve comparable performance as PFAS formulations (Nicol et al., 2022). In paper and board food packaging applications, adoption of non-fluorinated alternatives is hindered by a finished cost of 11% more compared to PFAS options (OECD, 2020). In architectural coating applications, initially, the polyurethane alternatives typically cost 26% less compared to PFAS-based coatings. However, with the PFAS-based coating offering more durability and less degradation over time, the total cost for the polyurethane alternative would be 16% more than the PFAS-based coating (OECD, 2022b). The desire to maintain profit margins and low-cost outputs with high performance and durability will continue to limit adoption of non-fluorinated alternatives across many industries. Without regulations in effect that require manufacturers of PFAS- and PFAS-containing products to address PFAS contamination in the environment, the market price for PFAS is less expensive, but the societal cost is not addressed.

Regulatory Factors

> Some regulators have worked to phase out all PFAS as a class instead of individual PFAS in an attempt to avoid regrettable substitution—when an equally concern chemical is used to replace an existing chemical of concern.

As discussed previously, the two of the most well-studied PFAS—PFOS and PFOA—are the target of regulations globally. The number of unregulated PFAS continue to dwindle as regulators slowly push to phase out all PFAS as a class instead of individual PFAS. This is intended to avoid having to study and understand every individual chemistry and to avoid regrettable substitution, which is when an equally concerning chemical (that may not be as well-studied) is used to replace an existing chemical of concern. An example of this was seen when concern over PFAS began emerging. Within the last 20 years, many companies switched from the original eight-carbon (or C8) to six-carbon (C6) PFAS alternatives believing they improved environmental and health performance. However, studies have shown that C6 chemistries have worse environmental and health performance in many cases. Many companies are now investing time and resources into identifying another solution that hopefully will not warrant reformulation yet again in a few years.

Legislation that is directly or indirectly relevant to PFAS plays a role in the current environment surrounding PFAS substitution. As an example, the coatings industry has historically used PFAS as a wetting agent to provide leveling and spreading properties that consumers expect from quality coatings. In recent years, the coatings industry is shifting to water-borne systems to reduce volatile organic compounds as a result of regulatory restrictions (Kumar & Bhattacharya,, 2020). This puts increased demand on coatings as water has a higher surface tension than organic coating solvents, and therefore wetting of substrates becomes a major challenge. At the same time, regulatory bodies are restricting the use of PFAS, which has been relied upon to address this deficit. However, one expert stated that although some industries face challenges in eliminating PFAS, regulation can be a driver for innovation and progress (Name withheld, 2023b).

Other Non-Price Factors

Performance

Experts noted that the main challenges of finding PFAS alternatives in packaging is identifying alternatives that are viable, scalable, and safer than PFAS (Name withheld, 2023d; Name withheld, 2023c). In some applications, PFAS can be readily substituted with minimal impact on perceived performance, but for others (e.g., nonstick cookware, water-repellent clothing, surface coatings) the standard for performance expected by consumers makes PFAS not as easily replaced. This has become a major barrier to substitution for many product developers because they face the challenge of impending legislation and consumer backlash alongside the need to maintain strong performance. When considering substitution of PFAS, various performance factors must be considered and evaluated.

The nonstick properties of PFAS are due to their unique chemical structure, which includes a long-fluorinated carbon chain. The fluorinated carbon chain in PFAS is highly hydrophobic, meaning that it repels water and other polar molecules. This hydrophobicity also makes the PFAS highly resistant to wetting, which is why they are used in nonstick coatings for cookware and other products. When a nonstick coating made with PFAS is applied to a surface, it forms a thin layer of highly water-repellent material. This layer prevents food and other substances from sticking to the surface, making it easier to clean and reducing the need for cooking oils or other lubricants.

The same properties that make PFAS resistant to wetting also allow it to spread uniformly across a surface in a level layer when used in applications such as firefighting foams and cement. PFAS function in firefighting foams by quickly spreading out and forming a thin, water-repellent film that seals off the fuel source from oxygen, effectively smothering the fire. The PFAS molecules in the foam help to stabilize the foam and prevent it from breaking down or dissipating too quickly. In cement applications, PFAS enable the mixture, when poured, to effectively level-out to form a uniform surface or layer.

PFAS are also known for their ability to withstand harsh conditions, such as high temperatures, chemicals, and abrasion. Thus, when replacing PFAS, it is vital to ensure that the alternative material or coating can provide similar durability under the intended conditions of use. This requires careful consideration of the mechanical, thermal, and chemical properties of the alternative material or coating.

PFAS-Based Alternatives

Many industries have struggled to find replacement chemistries for PFAS. Although short-chain fluorinated alternatives have a lower potential for bioaccumulation in living organisms than their long-chain counterparts, they are not necessarily any safer than long-chain PFAS. Studies have shown that some short-chain fluorinated alternatives, such as PFBS and PFHxS, can still have negative effects on human health and the environment. These impacts can include developmental and reproductive toxicity, liver damage, and immune system effects.

Furthermore, although short-chain PFAS may be less persistent in the environment than long-chain PFAS, they can still accumulate in soil and water and have the potential to contaminate drinking water sources. In addition, the use of short-chain fluorinated alternatives may also contribute to the overall production and release of PFAS into the environment, because the production of these chemicals can result in the release of long-chain PFAS and other related substances.

Overall, although short-chain fluorinated alternatives may have some advantages over long-chain PFAS, they are not necessarily any safer and may still pose risks to human health and the environment. Therefore, it is important to continue to explore and develop non-fluorinated and alternatives to PFAS to reduce the risks associated with these chemicals.

Trends in PFAS Substitution (PFAS and Non-PFAS Substitutes)

PFAS substitution is highly dictated by the desired benefits sought by users, including corrosion resistance, abrasion resistance, hydrophobicity, leveling, spreading, and wetting. The ability for PFAS to enable these benefits is through the modification of surface tension properties when formulated into a system or when applied to a surface of an object or material. When observing substitute chemistries and materials emerging on the market to take the place of PFAS, many of them exhibit the same ability to modify surface tension. The primary chemistries seen emerging on the market as potential substitutes for PFAS include silicones and siloxanes, anionic surfactants, nonionic surfactants, branched polymers, and hydrocarbon-based solutions, with the latter two being less common, and more information as follows:

Silicones and Siloxanes. Silica-based coatings, including silicone polymers comprised of silanes and siloxanes, are commonly used as alternatives to PFAS in various applications, including paints and coatings, textiles, food packaging, cosmetics, and other applications due to their low surface tension. Although a common alternative to PFAS for various applications, consistent issues with gaps in performance and costs still exist.

Anionic Surfactants. Sulfosuccinates have emerged as an alternative to PFAS in water-based varnishes and other applications for their low surface tension and ability to enable wetting and leveling properties. Other anionic surfactants including alkyl ether sulfates (metal plating applications) and ether sulfonates (oil recovery) are also considered potential alternatives due to their low surface tensions.

Nonionic Surfactants. Nonionic surfactants are also emerging as potential alternatives to fluorinated surfactants due to their low surface tension and ability to confer spreading, leveling, and wetting properties. Specifically, acetylenic diols, ethoxylated alcohols, and alkoxylated alcohols are being marketed for use as replacements in water-borne coatings including paints, varnishes, flooring, and ink systems.

Branched Polymers. Star-shaped or dendritic polymers based on polyesteramides and polyamidoamines, and sometimes compounded with organo-silicone polymers are emerging for use in high-performance coating applications as they allow for increased surface modification and use of functional groups to enhance dispersion and reduce surface defects.

Hydrocarbons and Other Organics. Both anionic and nonionic aliphatic alcohols are used as alternatives for PFAS in industrial cleaners for their ability to be effective wetting agents. Anionic aliphatic alcohols are typically favorable replacements for detergent and cleaning agents, whereas nonionic alcohols are favorable replacements for defoamers and emulsifiers. Meadowfoam oil is used to replace PFAS in ski wax applications, and other alternative waxes based on paraffin and polyolefin chemistries, as well as inorganically-modified waxes, are used to replace PFAS in applications such as inks and toners, floor coatings, paper board and food packaging, textiles, and cosmetics.

Other. Other surfactants such as zwitterionic and amphoteric surfactants, gemini surfactants, branched or star surfactants, biosurfactants (e.g., rhamnolipids and sophorolipids) pyrrolidone, and surfactants blends (e.g., viscoelastic and the use of binary surfactant systems) are emerging as potential alternatives to PFAS in a variety of industries, though these chemistries are primarily discussed as alternatives in the oil and gas industry for recovery operations. Additionally, graphene as well as ceramics such as boron nitride, aluminum oxide, silicon dioxide, and titanium dioxide have demonstrated potential as replacements in both academic research as well as on the market for applications such as powder coating and lubrication.

BRAND PACKAGING INDUSTRY VETERAN & RETAIL PACKAGING ENGINEER

Key Point: The retail packaging industry is moving toward phasing out PFAS but finding suitable alternatives that comply with varying state regulations and in a limited timeframe is a challenge.

- Current alternatives have not been vetted for safety thoroughly enough through the R&D process, because regulators did not give enough time.
- There is evidence that certain alternatives in use are just as harmful to human health as PFAS.
- In the retail packaging industry, replacing PFAS is not so much of a challenge as identifying where PFAS is in the supply chain. At times, PFAS was found in unexpected products (e.g., metal closures, stretch films, and labels). Collaborating with suppliers to identify sources of PFAS is necessary.
- The definition of PFAS as a processing aid need to be standardized. Some manufacturers intentionally embed PFAS into materials, whereas some use PFAS on manufacturing equipment, which exposes products to PFAS through contact. Both examples count as processing aids, complicating regulation compliance.
- Another challenge with compliance is that it is difficult to track PFAS in products that are already on store shelves. A sell-through clause, where industries are permitted to sell products manufactured before a prior date, in regulations would help industries phase PFAS out of packaging. PFAS in recycled content in packaging also needs to be considered in regulations.
- Retail packaging industry stakeholders know of the negative human health impacts of PFAS. However, there are usually very low concentrations of PFAS in packaging, posing a lower health risk than products such as cookware and firefighting foams. PFAS exposure is a health crisis, but not because of exposure from packaging.
- Consumers are usually concerned with exposure to bisphenol A (BPA) rather than PFAS. Activists and regulators are driving change more than consumers in eliminating PFAS.
- During the next 5–10 years, the industry will keep moving toward finding PFAS alternatives. Larger manufacturers have been moving in this direction to comply with EU regulations. Small to medium enterprises will face more challenges and take more time to phase out PFAS.

4.3.4 Data Gaps, Limitations, and Uncertainties

The regulatory landscape is continually changing both domestically and internationally, as illustrated with the regulations proposed and finalized from 2021 to April 2023 at the federal and international levels, including, but not limited to, those listed in **Table 4-12**.

Table 4-12. Snapshot of Federal and International PFAS Regulations Proposed or Finalized in 2021–2023.

Finalized/ Proposed Date	Level	Amended Law/Regulation	PFAS Type	Description
		United States Federal Regulations		
May 2021 *Proposed*	United States	–	Class of PFAS	Prohibit procurement, purchase, and sale by the Department of Defense of certain items containing PFAS
November 2021 *Proposed*	United States	Federal Food, Drug, and Cosmetic Act	Class of PFAS	Prohibit the delivery or introduction of food packaging containing intentionally added PFAS into interstate commerce
September 2021 *Proposed*	United States	CERCLA	PFOA, PFOS	Designate PFOA and PFOS as hazardous substances
December 2021 *Final*	United States	SDWA	29 PFAS	Undertake nationwide monitoring for PFAS in drinking water under the fifth Unregulated Contaminant Monitoring Rule
January 2023 *Proposed*	United States	TSCA	330 inactive PFAS [a]	Establish a Significant New Use Rule to prevent anyone from resuming use of inactive PFAS without EPA review
March 2023 *Proposed*	United States	SDWA	PFOA, PFOS, PFHxS, PFBS, PFNA, GenX Chemicals	Establish legally enforceable levels and health-based, non-enforceable goals for six PFAS in drinking water
		International Regulations		
August 2021 *Proposed*	Member States of Stockholm Convention	–	Long-chain perfluorocarboxylic acids	Consider long-chain perfluorocarboxylic acids for consideration under the Stockholm Convention on Persistent Organic Pollutants
October 2022 *Final*	Members States of Rotterdam Convention	–	PFOA	Amend Annex III to include PFOA, its salts and PFOA-related compound
February 2023 *Proposed*	European Union	REACH	Class of PFAS	Reduce PFAS emissions into the environment and make products and processes safe for people

Notes: CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act.

[a] Inactive PFAS are chemicals that have not been imported or manufactured in the United States for many years. The active or inactive designation of chemicals is under TSCA.

Whereas federal and international-level regulations have largely focused on reductions of PFAS in environmental media (e.g., drinking water), state regulations have rapidly expanded to reductions of PFAS in consumer products. While indexing policies, we only summarized the international regulations that exceeded the standards set forth in the United States, which were largely regulations across the European Union. However, because exhaustive searches were not conducted to index all regulations, but rather trends, the results may not be indicative of a lack of PFAS regulations outside the United States and European Union.

As the regulatory landscape changes, there are challenges to be addressed including how to regulate PFAS—as a class, subclasses, or one-by-one—as well to how PFAS, “intentionally added,” and “unavoidable use” are defined. Additionally, from the manufacturer and consumer perspectives, it leads to the question of what substitutes for PFAS will provide comparable cost and performance. Many of the alternatives to PFAS have not been thoroughly tested for their performance in various applications. There is a need for more research to evaluate the performance of these alternatives and identify any potential drawbacks or limitations.

In addition to performance, several other aspects of alternatives have yet to be fully understood, including durability, environmental impacts, and safety. For instance, currently proposed alternatives may break down into substances that also have adverse effects to human health and the environment; it is critical to assess potential breakdown products to avoid regrettable substitution. Furthermore, consumer awareness and education of PFAS and its alternatives have yet to be addressed. Without increased consumer knowledge of PFAS and its effects and the performance and potential of its alternatives, consumers may be resistant to the shift.

4.4 Potential Exposure and Human Health Risks

4.4.1 Summary of Evidence Sources

KEY POINTS

- Most PFAS are persistent, and many are bioaccumulative—meaning they can accumulate and magnify through the environment and food chains, resulting in many routes for human exposure and prolonged timeframes for exposure. PFAS can also remain in the body long after exposure stops and can build up in the body over time.
- Ingestion of contaminated drinking water and food is the main human exposure pathway to PFAS. Additional research is needed for other exposure pathways, namely dermal absorption and inhalation.
- Exposure to PFAS are associated with a range of adverse health effects in the liver, immune system, early-life development, and cardiometabolic system. There is also growing evidence for endocrine disruption and reproductive effects. Several PFAS are associated with cancers.
- Infants, children, and pregnant and lactating persons can be more highly exposed to PFAS due to greater ingestion of water by body weight and are more susceptible to adverse health effects.
- PFOA and PFOS are the most thoroughly studied PFAS in the health and toxicity literature; the health effects evidence overall is challenged by how many PFAS exist (thousands) and traditional approaches to toxicity research.

Tier 1 Evidence: Authoritative Agencies

Tier 1 evidence was identified from various authoritative sources (see **Appendix D**). Several authoritative agencies conducted reviews to support exposure-specific mandates that are not directly under CPSC’s jurisdiction (e.g., drinking water, food); however, these sources still provide high-quality evidence syntheses and summaries on several overarching PFAS topics, particularly on toxicity and human health risks. Often, different branches or offices of key agencies will conduct distinct reviews of the available evidence. Agency and office priorities naturally differ for which compounds or subclasses are relevant for their decision-making mandates or research areas. This has led to an extensive, but patchwork set of available, authoritative evidence reviews across the PFAS family—see, for example, the similar-but-distinct scope of publications from various offices of U.S. EPA, which were heavily cited in this white paper (see **Appendix D**).

Tier 2 Evidence: Peer-Reviewed Literature

Tier 2 evidence included peer-reviewed literature focused on 1) exposure and 2) toxicity and risk. After prioritization and screening (detailed in **Appendix A**), 610 studies were considered relevant for characterizing exposure in this white paper and 346 studies were considered relevant for toxicity and risk. Many of these studies were used to understand the state of exposure to PFAS and associated human health risks and summarized in this section, whereas the remaining studies and relevant tags are indexed in the database (*PFAS Literature on Exposure, Toxicity, and Health Risk.xlsx*). Across the studies, less than 100 PFAS were identified with the majority of PFAS classified as perfluoroalkyl substance – consistent with policies and regulations discussed previously.

4.4.2 PFAS Exposure Sources and Pathways

Sources of Potential PFAS Exposure

PFAS are pervasive throughout the environment, residential settings, and occupational and manufacturing settings. PFAS exposure can also arise from transfer in utero and through breastfeeding. Testing as early as the 1999–2000 sampling period for the National Health and Examination Survey (NHANES) detected PFAS in 98% of the serum samples collected to represent the U.S. general population (ATSDR, 2020). Mean serum levels of PFOA and PFOS have been generally declining in the United States as these long-chain PFAS are phased out of production and use. However, PFOA and PFOS can still present exposures due to their persistence in the environment and importation of consumer and industrial products from countries still producing and using PFOA and PFOS. Despite declines in the general population, even at low levels of exposure, PFOA and PFOS can pose risks to human health (U.S. EPA, 2023d; U.S. EPA, 2023e). In addition, populations are still exposed to numerous other PFAS and mixtures of PFAS. Although there are thousands of known PFAS, only a few dozen are commonly assessed in the exposure and health literature, with PFOA and PFOS being the most well-studied. Furthermore, unidentified organofluorine (UOF) has also been detected in human biospecimens, environmental media, and consumer products, likely representing additional PFAS for which risks are unknown (Aroet al., 2021).

From Source to Exposure. Although there are a variety of point sources, these initial sources become part of the PFAS lifecycle in the environment and subsequently may be found in air, crops, groundwater, soil and sediment, and surface waters.

Potential PFAS exposure is most well researched for the ingestion pathway, especially from drinking water and foods. Other pathways of potential PFAS exposure, such as air inhalation or direct contact, are less well understood.

In the outdoor environment, PFAS sources are commonly categorized as *point* or *non-point sources*. Point sources are typically localized areas of PFAS generation or concentrated use that can release PFAS into environmental media, such as ground and surface water, ambient air, and soil. Common point sources of PFAS can include fluorochemical manufacturing facilities, product manufacturers, airports, firefighting facilities, and wastewater and drinking water treatment plants. Landfills can also serve as a localized source of PFAS releases into the environment, because PFAS-containing products break down and concentrate in landfill leachate, which can enter environmental media if improperly managed.

Non-point sources of PFAS include runoff from point sources and the land application of biosolids (e.g., sludge from wastewater treatment plants used as fertilizer), which can be highly concentrated in PFAS, and from which PFAS can enter the food chain.

The introduction of PFAS into the environment can have critical and complex downstream effects on human-relevant exposure scenarios; these interconnected concepts are discussed in more detail throughout this section and are illustrated in **Figure 4-23**. Although contaminated drinking water has been at the forefront of research and regulation globally, research continues to investigate other pathways (e.g., inhalation) and sources (e.g., indoor dust). In developing the drinking water health advisories for GenX and PFBS, the U.S. EPA included oral, inhalation, and dermal as potential exposure routes (U.S. EPA, 2022c; U.S. EPA, 2022d).

The proposed U.S. EPA Maximum Contaminant Level (MCL) for PFOS and PFOA in drinking water is 4 parts per trillion (ppt). To visualize this MCL in terms of time, consider a period of one trillion seconds. That represents approximately 31,710 years! In this case, 4 seconds out of 31,710 years would be the equivalent of 4 ppt PFAS in water.

Similar to the outdoor environment, the indoor environment can contain both point sources (e.g., consumer products and food) and non-point sources (e.g., air and dust). The indoor environment is considered in greater detail in the following sections.

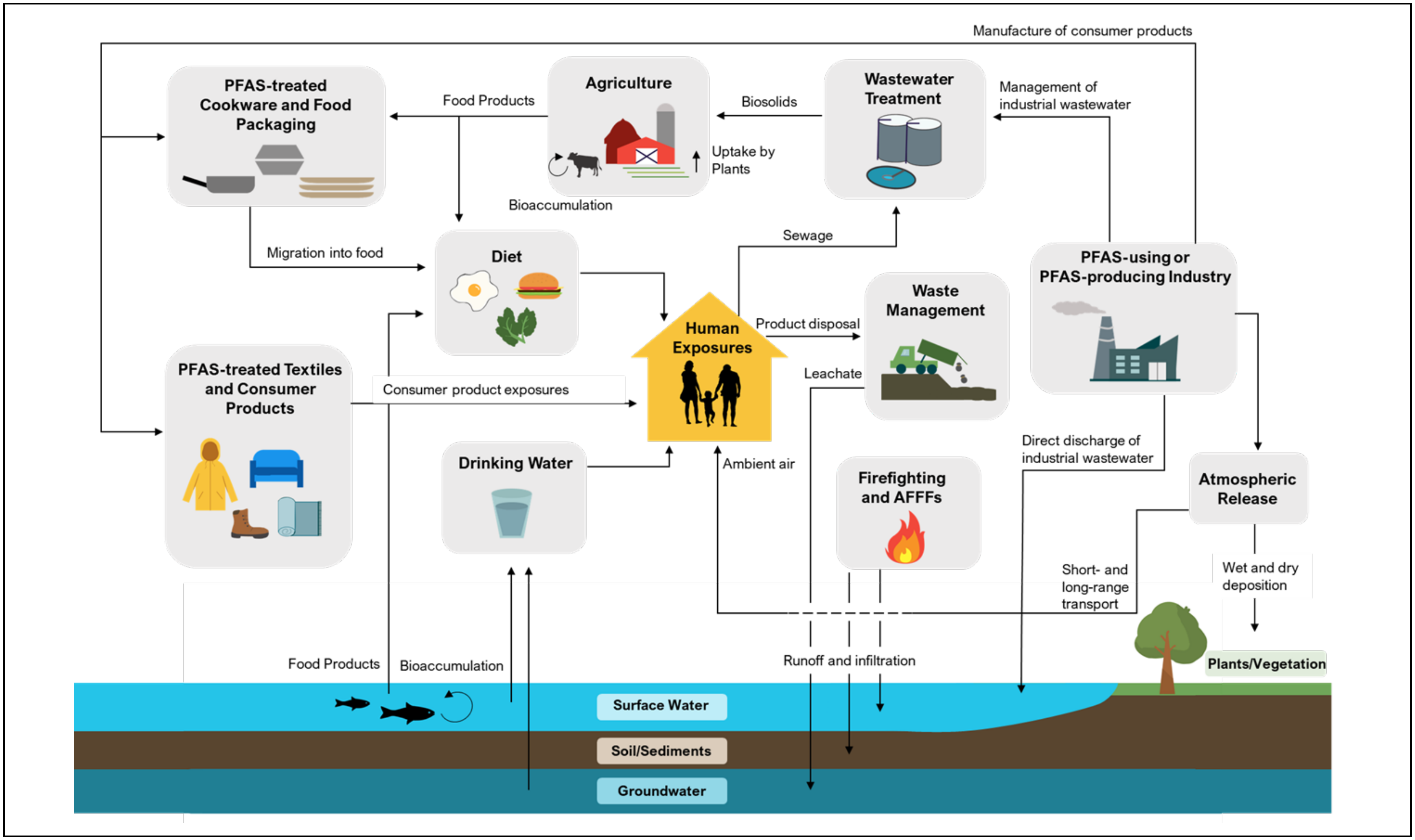
Given the many point and non-point sources of PFAS in the indoor and outdoor environments, the general population can be exposed to PFAS through various routes and sources.

TECHNICAL CORNER

A recent report by the National Science and Technology Council summarized the current availability and quality of information on exposure routes to the public and designated exposure to PFAAs via ingestion as having some information available (Joint Subcommittee on Environment, 2023). However, exposure to PFAS precursors or other PFAS via ingestion was designated as having limited or no information. Exposure to any PFAS via inhalation or dermal contact was designated as having limited or no information (Joint Subcommittee on Environment, 2023). Similarly, there is a lack of exposure studies with paired PFAS measurements in serum and in media other than drinking water and diet (DeLuca et al., 2022). There are significant knowledge gaps that exist in understanding all PFAS exposure scenarios.

Additionally, relative source contribution (RSC) is also of interest when assessing potential exposures. RSC is a calculation of an individual’s total exposure allocated to different sources; for example, if diet was to contribute half of total exposure to a chemical and drinking water was to contribute the other half of total exposure, then the RSC for diet would be 50% (U.S. EPA, 2023d; U.S. EPA, 2023e). In developing the drinking water health advisories for GenX and PFBS, the U.S. EPA also identified the following potential exposure sources: drinking water, ambient ground and surface water, industrial uses, air, soil, food, dust, consumer products, firefighting foams, biosolids, and sediment (U.S. EPA, 2022c; U.S. EPA, 2022d).

Figure 4-23. **Summary of Key Exposure Pathways throughout the PFAS Lifecycle**



Note: **Figure 4-23** focuses on high-level exposure processes and pathways across the PFAS lifecycle; for more detail on exposure sources and pathways related to the indoor environment and humans (i.e., the area in the center of this figure), please refer to **Figures 4-24** and **4-25**.

PFAS Exposure and Susceptible Populations

It is critical to account for susceptible populations when addressing exposure and subsequent risk of chemicals of concern, including PFAS. Susceptible populations are those who are at higher risk of exposure and/or health effects from chemical exposures. Susceptibility can be due to biological and/or exposure-related factors. Biological factors include age or life stage, genetic polymorphisms, race and ethnicity, sex, and other factors, whereas exposure-related factors can include disease status, geographic proximity to exposure sources, lifestyle, nutrition status, socioeconomic status, and more.

Age and Life Stage. Fetuses, infants, and children are considered susceptible populations given their age and life stage. Exposure in pregnant and lactating persons has serious implications for the fetus and infant, because PFAS can be transferred in utero and in breastmilk. Pregnant and lactating persons may have higher PFAS exposures than the general population due to drinking more water per pound of body weight during pregnancy and lactation, which can increase their PFAS body burdens if their drinking water supplies are contaminated. EFSA found that toddlers and young children had twofold higher PFAS exposure than adults, largely due to in utero or lactational transfer (EFSA Panel on Contaminants in the Food Chain, 2020). Children are particularly susceptible to the effects of PFAS exposure due to critical developmental stages that are sensitive to disruption from chemicals. Children also engage in more activities that can increase their PFAS exposure, such as crawling on floors and hand-to-mouth activities. Furthermore, children consume more food and water and inhale more air per pound of body weight, which generally increases their levels of chemical exposures compared to adults. For 2-year-old children, food is estimated to contribute approximately 31% for PFOA and 84% for PFOS (Egeghy & Lorber, 2011; Haug et al., 2011; Lorber & Egeghy, 2011). The number of times and intervals between births (i.e., parity) can also affect lactational exposure in infants, as higher levels of PFAS have been observed in first-time birthing parents (Barbarossa et al., 2013). Several key health effects with strong evidence bases also have been observed in fetuses and infants due to in utero or lactational transfer in utero or breastmilk, including low birth weight (see **Section 4.4.3**).

Mouthing. Additionally, for small children, non-dietary ingestion is likely to be an important pathway given their increased level of hand-to-mouth and object-to-mouth behaviors compared with adults; their proximity to the floor while crawling and playing on the floor can also contribute (Winkens et al., 2018). Hand-to-mouth and object-to-mouth behaviors can result in incidental exposure of dust and soil contaminated with PFAS. One study estimated that hand-to-mouth behavior contributed 40% of overall infant human exposure to PFOA and PFOS, whereas breast milk and dust ingestion contributed 45% and 15%, respectively, for PFOA, and breast milk, dust ingestion, and inhalation contributed 35%, 20%, and 2%, respectively, for PFOS (Trudel et al., 2008).

The Elderly and Beyond. Research into health effects for susceptible populations is strongest in fetuses, infants, children, and pregnant and lactating persons; there is significant uncertainty about other potentially susceptible populations, such as elderly populations. Because of historical use of PFAS and their capacity for persistence and bioaccumulation, elderly populations have likely experienced lifetimes of PFAS exposure and accumulation and may have specific health concerns given this unique life stage (Obeng-Gyasi, 2022). More research is needed on PFAS exposure and health effects over the life course and particularly in aging populations. There is also uncertainty in variability in potential susceptibility and exposure levels between different racial and ethnic groups, educational backgrounds, and income levels. Sociodemographic factors influencing PFAS exposures are an area of ongoing research, but likely relate to food access and dietary behaviors, housing characteristics and the built environment, water sources, and occupation types (Boronow et al., 2019; Obeng-Gyasi, 2022).

These are key data gaps that should be considered in the context of environmental justice concerns related to PFAS exposure and these topics have been identified as a high priority research need by EPA (U.S. EPA, 2023f).

Chronic Health Conditions. Lastly, certain health outcomes are known to change levels of PFAS in the body. This is particularly notable for impaired kidney function (e.g., decreased glomerular filtration rates) and early menopause. Although these health statuses are often considered in the context of assessing reverse causality in the epidemiology literature, the presence of chronic diseases or other health conditions could have implications for susceptibility to PFAS health effects and PFAS body burdens over time. Other internal and external health factors, such as pharmaceutical use or stress, could play a role in susceptibility to the health effects of PFAS exposure, given the suspected mechanisms underlying PFAS toxicity. See **Section 4.4.3** for more information on PFAS toxicity.

Potential PFAS Exposures in the General Population

Pathways for potential PFAS exposure in the general population include dietary and non-dietary ingestion, inhalation, and dermal absorption. Several studies indicate that food ingestion is the main route of exposure for PFAS (Egeghy & Lorber, 2011; Haug et al., 2011; Lorber & Egeghy, 2011; Sunderland et al., 2019; Poothong et al., 2020). Based on different scenarios for adults, food is estimated to contribute 63%–84% of the total intake of PFOA and 83%–99% of the total intake for PFOS (Egeghy & Lorber, 2011; Haug et al., 2011; Lorber & Egeghy, 2011). However, in studying 41 Norwegian women, (Haug et al., 2011) reported that the indoor environment (including air and dust) could contribute up to approximately 50% of total PFAS intake. Even in considering additional PFAS for total PFAS intake (PFOA, PFOS, and 13 additional PFAS), the median dietary intake still represented approximately 91% but ranged between 4% and 98% (Poothong et al., 2020). There continue to be several uncertainties in estimating intake due to limited knowledge on absorption rates, biotransformation rates, and other rates (Egeghy & Lorber, 2011; Haug et al., 2011; Lorber & Egeghy, 2011; Poothong et al., 2020).

Ingestion of Drinking Water, Dust, Food, and Soil. For the general population, ingestion is the most well-studied route of exposure to PFAS (NASEM, 2022). As described previously, the peer-reviewed literature on associations between exposure to drinking water contaminated with PFAS and health effects has increased significantly across the last decades.

There are inconsistent conclusions across the literature about whether FCMs contribute to significantly higher human exposure to PFAS (Susmann et al., 2019; Jogsten et al., 2009; Schaider et al., 2017).

Inhalation of Indoor and Outdoor Air. The importance of inhalation of indoor air was highlighted in a study that between 2018 and 2020 analyzed indoor air and dust in various environments: carpeted kindergarten classrooms, residences, and an apparel and outdoor gear store in northern California and carpet store, classrooms, laboratories, and university offices in southern Rhode Island. Overall, compositions and concentrations varied, likely based on the PFAS-containing products in each environment, but neutral PFAS were present at all locations and dominated by the volatile PFAS, FTOHs (Morales-McDevitt et al., 2021). Two FTOHs—6:2 FTOH and 8:2 FTOH—were the dominant PFAS in kindergarten classrooms and university rooms. However, FTOHs were detected only in carpeted rooms and laboratories.

Although PFAS have been detected in indoor air, information is limited for full exposure assessments. In a systematic review, DeLuca et al. (2022) identified two studies that reported on paired PFAS measurements in serum and indoor air. In assessing at least two of three PFAS (PFOA, PFNA, and PFOS), studies attributed 0.29%–4.01% of total PFAS exposure among pregnant women in Vancouver, Canada, from indoor air inhalation, and 0.20%–2.80% of exposure among children in Eastern Finland from indoor air inhalation (Balket al., 2019; DeLuca et al., 2022; Makey et al., 2017).

Dermal Absorption from Consumer Products, Dust, and Soil. Limited studies have investigated dermal absorption or uptake (or direct contact on skin) as an exposure route for PFAS. Dermal absorption is dependent upon several physicochemical properties of the compound (such as its molecular weight, partitioning coefficients, water solubility) (Ragnarsdottir et al., 2022). These properties vary across PFAS; however, studies on other halogenated organic pollutants, including brominated and chlorinated flame retardants, suggest that dermal absorption could contribute to total body burden (Ragnarsdottir et al., 2022).

Two studies estimated adult exposure to PFOA or PFOS via dermal absorption to contribute less than 1% of total exposure (Egeghy & Lorber, 2011; Lorber & Egeghy, 2011). Specifically for children, daily PFAS uptake via dermal dust absorption was estimated to be two orders of magnitude smaller than through dust ingestion (0.004 ng/kg body weight/day versus 0.26 ng/kg body weight/day) (Zheng et al., 2020).

RETAIL PACKAGING INDUSTRY VETERAN

- Water and humidity are significant vehicles for PFAS exposure to humans, along with air. Dermal exposure is something that the industry is beginning to investigate more as a pathway for contamination.

EUROPEAN ACADEMIC FOCUSED ON PFAS

- Dermal exposure is not the main exposure route. There is evidence that indoor dust may be a larger route for exposure.

Gestational and Lactational Transfer. Developing embryos/fetuses have an additional exposure route of importance: gestational and lactational transfer. Gestational transfer refers to transfer of PFAS from the parent to the child in utero via the placenta, and lactational transfer refers to the transfer of PFAS from the parent to the child via breastfeeding.

Studies have reported detection of PFAS in human breastmilk and umbilical cord blood, suggesting infant exposure to PFAS via breastfeeding and in utero (ATSDR, 2021). These two exposure pathways are particularly significant because early-life PFAS exposure is associated with developmental health outcomes as described in ***Section 4.4.3***.

TECHNICAL CORNER

Brief examples of studies reporting PFAS in human breastmilk and umbilical cord blood are mentioned below.

Among mother-child pairs in Ronneby, Sweden, in 2015–2020, PFOA and PFOS were detected in the majority (≥95%) of all three milk samples: colostrum (3–4 days postpartum), initial mature milk (4–12 weeks postpartum), and repeated mature milk (4–12 weeks postpartum) (Blomberg et al., 2023). PFOS and PFHxS had the highest median concentrations across all samples with median concentrations ranging 0.12–0.16 ng/mL for PFOS and 0.09–0.16 ng/mL for PFHxS (Blomberg et al., 2023).

Regarding in utero exposure, among singleton deliveries in Baltimore, Maryland, in 2004–2005, PFOA was detected in 100% of cord blood serum samples (median concentration 1.6 ng/mL), and PFOS was detected in more than 99% of samples (median concentration of 5 ng/mL) (Apelberget al., 2007). More recently, a study in Maoming, China, in 2015–2018 assessed legacy PFAS and “alternative” PFAS in birthing parent serum and cord serum samples; in serum samples, the highest median concentrations were of total PFOS (4.32 ng/mL), PFOA (0.99 ng/mL), and PFBA (0.70 ng/mL) (Cai et al., 2020). In cord serum, the highest concentrations were of total PFOS (1.93 ng/mL), PFBA (1.45 ng/mL), and PFOA (0.75 ng/mL). Additionally, alternative PFAS, such as PFBA and 8:2 chlorinated polyfluroalkyl ether sulfonic acid (Cl-PFESA), had higher transplacental transfers than PFOA and PFOS (Cai et al., 2020).

Potential PFAS Exposures from Consumer Products

Consumer behaviors (e.g., what consumer products are purchased and how often those products are used) are associated with concentrations of PFAS (as measured in matrices such as serum) in individuals. Specific consumer behaviors have varied across studies, and for adults have included frequencies of consuming certain food products (e.g., fish, meat, microwave popcorn), use of a certain brand-name dental floss and other personal care products, and having stain-resistant carpet or furniture as significant predictors of PFAS in serum (Wu et al., 2015; Jain, 2014). Specifically, among African American women, frequent consumption of prepared food in coated cardboard containers was cited (Boronow et al., 2019). In children, frequencies of consuming certain food products and wearing waterproof clothes were reported as predictors (Wu et al., 2015).

PRODUCT FORMULATION EXPERT

Consumer products that are close to anything that is ingested (e.g., cookware, food wrappers) have a greater risk for human exposure, whereas products such as clothing, coatings, and paints have lesser risk.

During the consumer use phase of a consumer product, potential emissions and migration of PFAS could occur from the following: abrasion, direct transfer to indoor surfaces, direct transfer to skin, migration into saliva, and volatilization to indoor air for more-highly volatile PFAS (DeLuca et al., 2021). As discussed previously, although other studies have estimated the contribution of different pathways, there is a knowledge gap in understanding the link between PFAS concentrations in products and the concentrations in indoor and outdoor environments (Sunderland et al., 2019).

A conceptual diagram of exposure sources and pathways related to common consumer products is shown in **Figures 4-24** and **4-25**.

Figure 4-24. Summary of Common PFAS Exposure Sources Related to Consumer Products

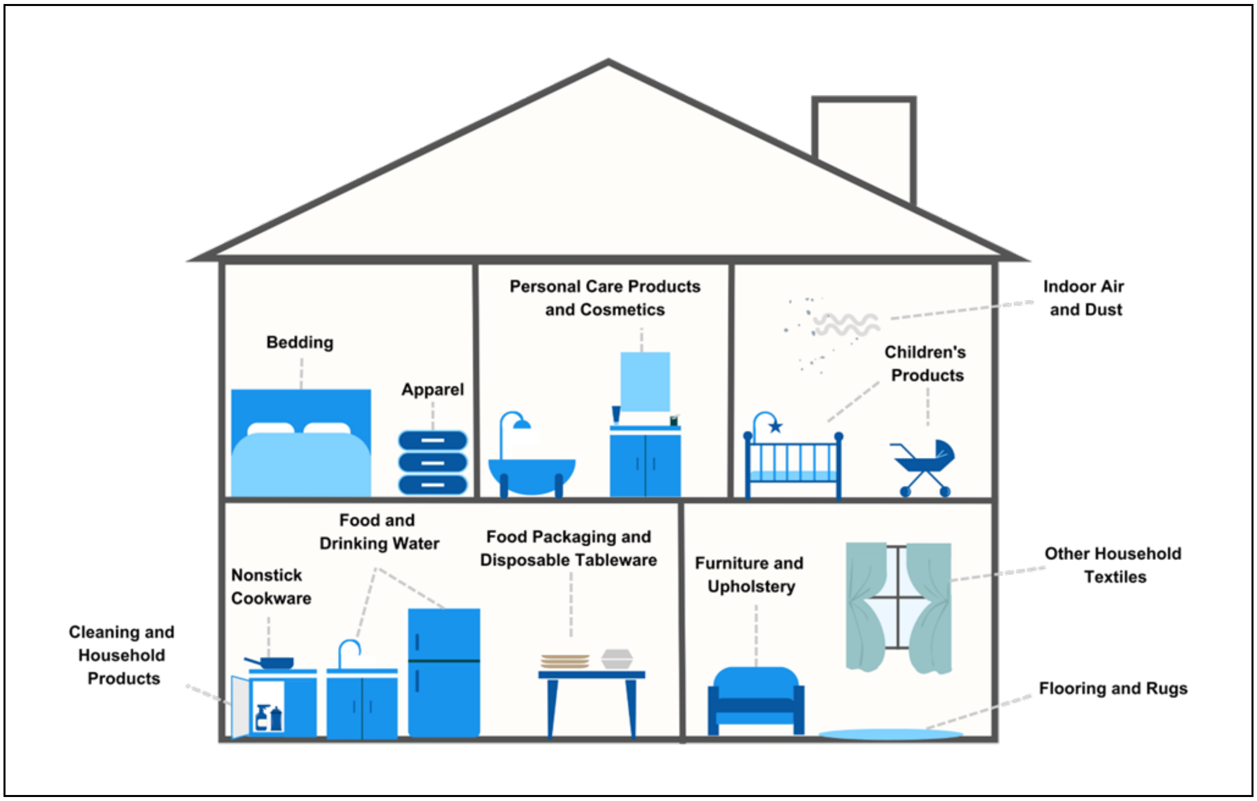
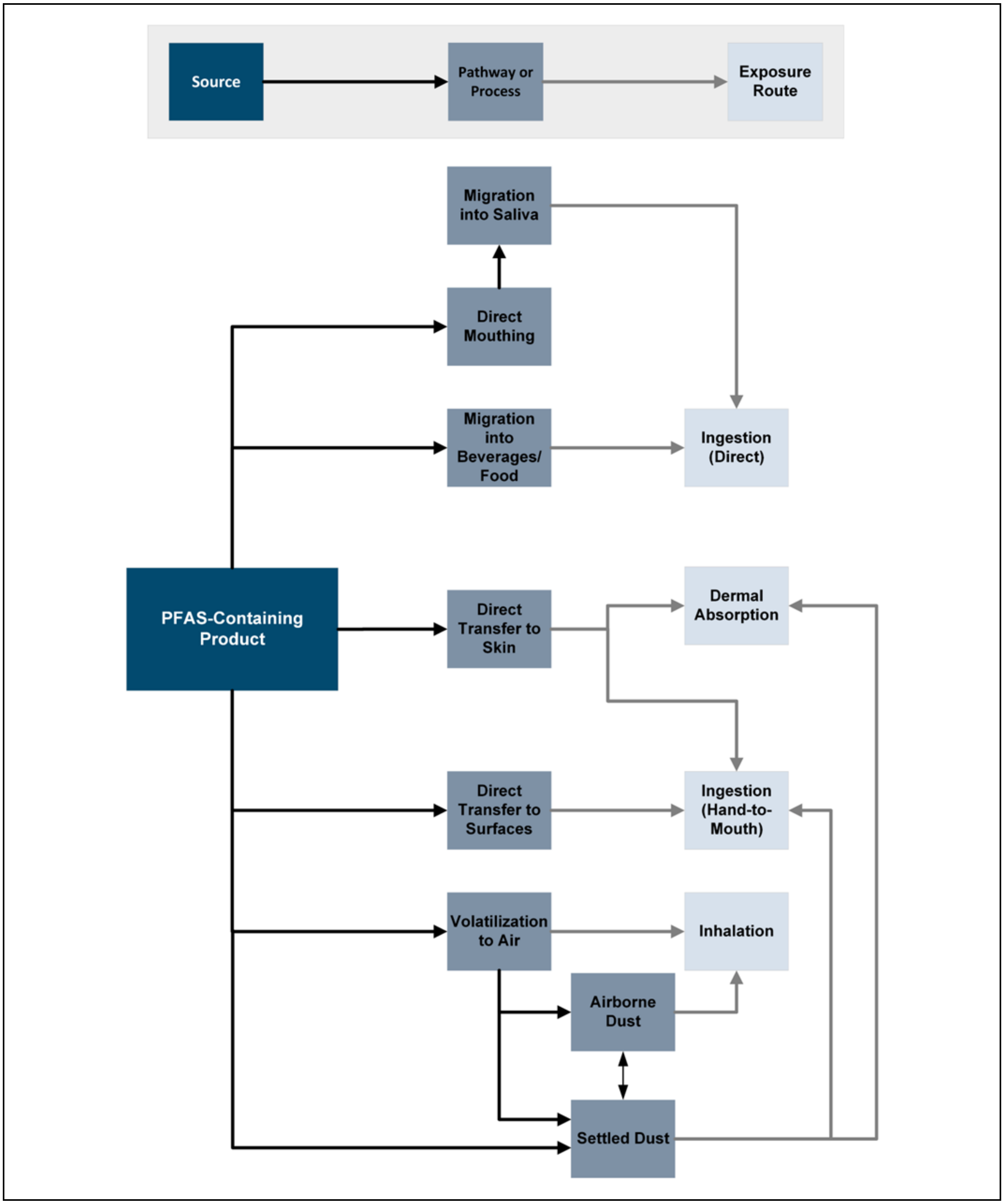


Figure 4-25. Summary of PFAS Human Exposure Pathways Related to Consumer Products



Source: Adapted from Eichler et al. (2020).

Clothing, Apparel, Jewelry, and Accessories. Non-dietary ingestion and dermal absorption are likely exposure pathways for consumers using fabrics and textiles. Exposure may occur from hand-to-mouth contact, mouthing (for infants and toddlers), and skin contact. For the former two—hand-to-mouth contact and mouth—migration testing is conducted to determine how much of a chemical is transferred from the product and into saliva or on skin. Migration testing conducted by the Danish EPA and Commission for Environmental Cooperation had differing conclusions: the Danish EPA reported that the composition of PFAS in artificial saliva and laundry water were significantly different than the composition of PFAS in the material initially assessed, whereas the Commission for Environmental Cooperation reported similarities between the compositions before and after the migration testing.

TECHNICAL CORNER

The Danish EPA assessed 15 products with PFAS-containing impregnating agents for a migration test using artificial saliva and eight products using laundry water. Among the products selected for the migration test using artificial saliva, the composition of PFAS in the artificial saliva was significantly different from the composition in the materials initially assessed. Although FTOHs accounted for much of the total content of PFAS in the materials, in general, the content in the artificial saliva was low. Composition in the artificial saliva was largely perfluoroalkyl carboxylates (e.g., PFOA) and FTSAs. Authors further noted that among the perfluoroalkyl carboxylates, there was a shift toward the shorter chains detected in the artificial saliva compared to the concentrations of the materials.

Among the products selected for the migration test using laundry water, the results were similar to those of artificial saliva, in which detected analytes largely consisted of acids: perfluoroalkyl carboxylates and FTSAs. The authors concluded that the results of the two migration tests were not significantly different.

The survey conducted by the Commission for Environmental Cooperation included migration testing using artificial saliva and laundry water, as well as artificial sweat. The PFAS migration to laundry water for the five tested items (adult outdoor jackets, sport jackets, and waterproof trousers) were consistent with the initial determination of PFAS; for instance, PFBS, 6:2 fluorotelomer carboxylic acid (FTCA), and PFBA were the highest concentrations for an adult outdoor jacket in the initial determinations (92, 35, and 32 ng/g, respectively) and were also the highest concentrations in the laundry water (59, 14, and 19 ng/g, respectively). Overall, total PFAS in wash fractions ranged between 38 and 330 ng/g. It should be noted that the testing simulated only one cycle of washing, rinsing, and spin-drying after its initial purchase.

Items determined most relevant for the migration tests to artificial saliva were baby bibs, children’s rainsuits, and waterproof baby-changing table mats. Total PFAS ranged 0.50–7.8 ng/g. Items for the migration tests to artificial sweat (adult outdoor jackets, children’s outdoor jackets, cycling globes, children’s gloves, winter gloves, and waterproof trousers) resulted in total PFAS between 0.04 and 100 ng/g. Authors noted critical limitations in the methodology for both initial PFAS determinations and migration tests and suggested future research to explore other methodologies.

As discussed in **Section 4.1.2**, weathering of consumer products, such as durable water-repellent clothing, over their lifespan can result in the degradation and migration of PFAS from the products. Subsequently, migration of PFAS from those products may constitute a direct exposure route to humans, such as through dermal absorption (van der Veen et al., 2020).

Containers and Packaging. Food contact materials (FCMs) are defined as packaging materials used for consumer items. In the EU, FCMs must be assessed for safety and inertness by the EFSA (European Commission, n.d.). This is intended to ensure that the materials do not 1) release their constituents into food at levels harmful to human health and 2) change food composition in terms of odor or taste. As part of the assessment by the EFSA, migration testing is conducted; certain substances are subject to specific migration limits. EFSA has published reports for seven PFAS between 2011 and 2016 (EFSA, 2011b; EFSA, 2011c; EFSA, 2011d; EFSA, 2012; EFSA, 2015; EFSA, 2016; EFSA, 2014). The seven PFAS are lesser known based on the literature but used as polymer production aids for manufacturing fluoropolymers used in FCMs. Using the worst-case migration levels of the substances, the EFSA Panel of FCMs, Enzymes, Flavourings and Processing Aids concluded migration to be negligible and subsequently not considered a safety concern for consumers.

SUSTAINABLE PACKAGING INDUSTRY VETERAN

Consumers are more likely to be exposed to PFAS from a fiber-based product, such as paper or textiles—especially if the product is exposed to moisture. The majority of PFAS exposure comes from liquid-based products, because PFAS is water soluble, which makes the molecules very mobile in water.

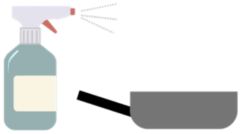
Additionally, in a study of 42 samples of food packaging materials including aluminum foil, beverage cups, popcorn packaging materials, wrappers, and others, authors concluded that based on the PFAS detected and quantified, there was probably no serious danger for consumers' health associated about PFAS contamination of the packaging materials (Zafeiraki et al., 2014).

As of 2018, the Denmark National Institute for Public Health and the Environment concluded that there are limited peer-reviewed publications on the migration of PFAS from FCMs or food contact substances (Dutch National Institute for Public Health and the Environment, 2018). However, more recently, researchers in academia and the U.S. EPA have assessed fluorinated containers (e.g., directly fluorinated high density polyethylene containers) as a source of PFAS migration into products. The U.S. EPA stated that PFAS may be formed and leached into the products stored in fluorinated high density polyethylene containers, which has been subsequently supported by other research (Nguyen, 2021; Hoponick Redmon et al., 2022). Although the U.S. EPA studies focused on pesticide products, directly fluorinated containers are also used for food packaging, household cleaners, personal care products, and other items (Whitehead & Peaslee, 2023). Although dietary intake is thought to be a major source of exposure to PFAS, exposure to PFAS-contaminated beverages and food may at least be in part due to PFAS migration from FCMs (Xu et al., 2013).

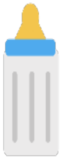
Plastic Storage Containers. Directly fluorinated high density polyethylene containers may be a source of PFAS migration into products. While dietary intake is thought to be a major source of exposure to PFAS, exposure to PFAS-contaminated beverages and food may at least in part be due to PFAS migration from FCMs in certain cases.

Cosmetics and Personal Care Products. Cosmetics and personal care products containing PFAS (e.g., lotions, sunscreens) are of concern due to direct application to human skin that may result in dermal exposure to those PFAS (Fujii et al., 2013). In a Danish EPA assessment on cosmetic products, dermal exposure scenarios were conducted for body lotion, color correcting cream and foundation, and concealer (Danish EPA, 2018). The cosmetic products were chosen based on the use of body lotion in large quantities over the entire body, and the other two products were determined to have the highest PFAS concentrations in previous analyses (Danish EPA, 2018). As mentioned previously, several parameters may influence dermal absorption of PFAS. The assessment considered different approaches, including 2% and 70% dermal absorption, that resulted in daily systemic exposure doses ranging between 8.45×10^{-7} to 2.96×10^{-5} mg/kg bodyweight per day (Danish EPA, 2018). Assessors underscored that the approaches were highly conservative, and exposure from several cosmetic products used at the same time should be considered (Danish EPA, 2018).

One study also reported potential PFAS exposure from absorption through tear ducts, in the case of mascara, or inadvertent ingestion of cosmetics such as lipstick (Whitehead & Peaslee, 2021). However, according on our knowledge, studies have yet to investigate PFAS absorption through tear ducts.



Household Products. The Norwegian Environment Agency reported on specific PFBS-containing consumer products and potential exposure pathways (Lassen et al., 2017). Products included agents for oil, water, and stain-repellent protection of fabrics, carpets, leather, and other items, and surfactants for inks, paints, waxes, and more, and exposure pathways included dermal absorption and inhalation. More specifically, for inks, paints, or waxes that contain surfactants, a consumer could be dermally exposed in the cleaning of equipment used to apply the product and/or cleaning of a spill. For products applied as an aerosol, a consumer could be exposed via inhalation. Additionally, coatings and paints may result in evaporation of the volatile PFBS-related impurities; therefore, the consumer could be exposed via inhalation.



Potential PFAS Exposures from Children's Consumer Products. As mentioned previously, hand-to-mouth and object-to-mouth behaviors can result in incidental exposure of PFAS, which happens more often for children. Additionally, when discussing the presence of PFAS in children's clothing, dermal absorption has been considered to contribute, at least in part, to PFAS exposure for children, as well as textile-to-mouth contact (Kotthoff et al., 2015). One report estimated daily intake via dermal absorption to 0.0002–222 ng/kg bodyweight per day but noted uncertainties in the input values such as the daily migration rate of non-polymeric PFAS from textiles to skin and the fraction of PFAS penetrated into the skin (Xia et al., 2022).

Authors of one study suggested that potential dermal absorption of chemicals released specifically from car seats could be significant (Wu et al., 2021). Shorter-chain PFAS (e.g., PFOA, PFOS, and PFBA) were readily extracted from fabric samples using synthetic sweat (Wu et al., 2021).

With respect to increased hand-to-mouth activities and increased time close to carpets, both carpets and indoor dust can be important exposure sources to PFAS for small children (Wu et al., 2020). For children ages 2–6 years who attended childcare centers, exposure scenarios for 17 PFAAs were estimated; total estimated daily PFAA intake via dust ingestion was reported as 0.023, 0.095, and 1.9 ng/kg body weight per day for low-, intermediate-, and high-exposure scenarios, respectively (Wu et al., 2020). For comparison, as indicated above, the EFSA established a TWI for the sum of four PFAS (PFOA, PFOS, PFHxS, and PFNA, all PFAAs, of 4.4 ng/kg body weight per week (equivalent to about 0.63 ng/kg body weight per day) (EFSA Panel on Contaminants in the Food Chain, 2020).

For considering exposure to PFAS through foods, one recent study of 112 baby foods (categories comprised of meat, fish, fruits and vegetables, and cheese) reported none of 16 targeted PFAS were found with concentrations above the limit of detection (Nobile et al., 2020). These results are in agreement with the food for infants and small children analyzed for PFOA and PFOS in a report by EFSA (2011a). However, EFSA noted limitations of the study related to relatively high limits of quantification for PFAS in baby food and small sample size.

A more recent study, published in 2023, analyzed infant formula and baby food for 14 PFAS and estimated the dietary intake of four PFAS (PFOA, PFHxS, PFNA, and PFOS) to compare to the TWI established by EFSA, which considers the sum of PFOA, PFOS, PFNA, and PFHxS. Concentrations of the 14 PFAS were low, and the dietary intake of four PFAS was negligible compared to the 4.4 ng/kg body weight TWI. However, like EFSA, the authors underscored the need for more sensitive methods (Mikolajczyk et al., 2023). Overall, advances in analytical methods are needed to further understand potential PFAS exposures from children's consumer products.

In both general consumer and children's products, PFAS are prevalent in stain- and water-resistant outerwear. Clothing is often worn for extended periods of time with direct contact with the skin, and therefore, has greater potential for direct children's exposure.

Occupational Exposures to PFAS

Workers handling and manufacturing PFAS and PFAS-containing products are often highly exposed individuals as compared to the general population. Workers can encounter products or exposure scenarios with very high concentrations of PFAS, and/or encounter PFAS-containing products or exposure scenarios more frequently and over a longer period of time, all of which can increase cumulative exposures and internal body burdens. Although occupational exposures are often considered distinct from the general population, the continued production and use of PFAS-containing products throughout society means the demands and market trends of the general population drive exposures in occupational populations. Occupational exposure to PFAS can occur in settings that are perceived as traditional environments for occupational exposures, such as fluorochemical manufacturing facilities, other industrial manufacturing facilities, and in emergency response industries—but occupational exposures can also occur in commercial, recreational, and residential settings.

There are 21 reported industry sectors where PFAS were used or are used currently, including biotechnology, chemical, pharmaceutical, textile production, food production industry, and others. An additional 43 use categories were also reported where PFAS were or are employed; use categories included firefighting foam and sports articles (Glüge et al., 2020). Fluorochemical plant workers, firefighters (airport and suburban), and professional ski waxers have been identified as occupational workers exposed to PFAS. Additional occupations are likely subject to high exposures to PFAS, but publicly available data are limited on other occupations (Lucas et al., 2022). With bans on certain consumer products and other regulatory trends, it is critical to also consider the conditions of those working closely with the chemicals and/or PFAS-containing products.

Serum PFAS levels of firefighters and professional ski waxers were reported as similar or higher than serum PFAS levels of fluorochemical workers; all three occupational groups had higher levels than the general population according to National Health and Examination Survey data (Lucas et al., 2022).

Among firefighters, AFFFs are of particular concern. AFFFs are complex mixtures of surfactants, including PFOS until it was largely phased out, used to extinguish fires. The fluorinated surfactants within the mixtures are chemical and thermally stable, making them particularly persistent in the environment. Exposure to PFAS and health risks have been investigated among subgroups of firefighters due to their frequent use of AFFFs when responding to emergencies and training. In addition to potential exposure to PFAS via ingestion of contaminated drinking water and food, firefighters are also exposed via dermal absorption, ingestion and/or inhalation of AFFF, dust, gear textiles, and/or smoke (Rosenfeld et al., 2023). Studies have found:

- Reported serum levels of PFOS approximately 6–10 times higher in firefighters in Australia compared to the levels in the general population in Australia and in Canada (median/mean of 66/74 ng/mL compared to median of 6.8 ng/mL in Canada and mean of 12 ng/mL in Australia) (Rotander et al., 2015).
- Reported serum levels of PFHxS approximately 10–15 times higher compared to the general population (median/mean of 25/33 ng/mL compared to median of 1.7 ng/mL in Canada and mean of 3.2 ng/mL in Australia) (Rotander et al., 2015).

Among professional ski waxers, application of glide wax and kick/grip wax is of concern. As discussed briefly in **Section 4.1.1**, the prevalence of PFAS in ski wax and its direct release into the environment from professional and recreational skiing led to the ban of fluorocarbon-based waxes in competitions by several entities (Fang et al., 2020; Carlson & Tupper, 2020). In addition to the environmental effects of the ski wax, it is also an occupational hazard (Freberg et al., 2013; Nilsson et al., 2013). PFAS exposure among ski waxers often exceeds the general population, with exposure to inhalable aerosols and respirable aerosols possible throughout the application of waxes (Freberg et al., 2013; Nilsson et al., 2013). Aerosols were largely characterized by FTOHs (including 6:2, 8:2, and 10:2 FTOHs) and volatile PFAS (Nilsson et al., 2013). Notably, throughout World Cup events in 2007–2010, occupational exposure standards were not in compliance for the professional ski waxers (Nilsson et al., 2013).

Although the literature focuses on a small set of occupational exposure scenarios, evidence is mounting for occupational exposure to PFAS in more commercial or residential settings. For instance, products used for professional floor stripping and waxing often use PFAS in their formulations, which can expose the worker to inhalable or volatilized PFAS during the application process (Zhou et al., 2022). More research is needed to characterize and quantify occupational exposure scenarios outside of the traditionally considered industries described previously. Furthermore, research is also needed to characterize the nature and extent of potential “take-home” exposures related to occupational PFAS exposures. Take-home exposures occur when workers inadvertently bring home the chemicals they are exposed to at work, such as when work clothes are washed with the household’s laundry, or when work shoes or uniforms are worn in the house. Such scenarios are poorly characterized for PFAS but could be important to consider in the context of children’s exposure in particular.

4.4.3 Current Knowledge on PFAS Toxicity

Introduction

Over the last decade, research and associated literature has rapidly increased on PFAS toxicity. Health effects and toxicity are of primary concern for non-polymer PFAS, which are water-soluble, highly mobile, and bioavailable. In contrast, polymeric PFAS are generally inert and considered less toxic than non-polymer PFAS (Henry et al., 2018), although emerging research in this area indicates there may be health concerns associated with some polymers (Lohmann et al., 2020). Furthermore, non-polymer PFAS can be used in the production of polymer PFAS, so the continued use of polymer PFAS in finished products contributes to human exposure of the more toxic non-polymers through production and waste management processes. The health risks of PFAS can be also considered in the context of carbon chain length, and in the context of "legacy" versus "replacement" chemicals, as discussed throughout this section (Lohmann et al., 2020).

The literature base for PFAS and health risks is characterized by vast amounts of information across the class; however, the quality, quantity, and consistency of publicly available information varies between chemicals and health outcomes. Within the broad class of PFAS, health effects research has focused on PFAAs. Indeed, PFOA and PFOS are the most extensively studied legacy PFAS compounds in the context of health risks (with PFNA and PFHxS to lesser extents), whereas the evidence base is sparser for other PFAS compounds. The large number of chemicals and scarcity of publicly available evidence for most chemicals *within* the class presents challenges for evaluating and assessing health effects and risks *across* the class. Toxicity and health effects are expected to vary between PFAS to a certain degree due to the diversity of chemical structures and properties within the class; however, the persistence of PFAS remains a concern across the class and many PFAS are expected to share similar target systems and health endpoints due to similar fundamental chemical properties.

- **Non-polymer PFAS** are defined as PFAS of only one unit (monomer). They are considered more toxic, in part because their bioavailability and water solubility make it more likely for the chemicals to enter and accumulate in the human body.
- **Polymer PFAS** are defined as PFAS with a recurring sequence of one or more types of units (monomers, forming polymers). While they are generally thought to be less toxic and inert, recent research indicates that there may still be health concerns.
- **"Legacy" PFAS compounds** refer to PFAS with eight or more carbons. Strong evidence of health concerns led to **"replacement" PFAS compounds** that contained fewer carbons and shorter chain lengths.

Although standardized approaches have not been developed—and toxicity is expected to vary across the class (Andersonet al., 2022)—many researchers and decision-makers are exploring class-based approaches or various grouping strategies for analyses and regulation, given several considerations (Konkel, 2021; Bălanet al., 2021; Cousins, 2020a; Cousins, 2020b; Kwiatkowski et al., 2020; Wang et al., 2017; Wang et al., 2015), including:

- **Exposure to PFAS mixtures** – The general population is exposed to complex and variable mixtures of numerous PFAS and individual contributions of specific PFAS compounds can be difficult to separate in most human-relevant exposure scenarios;
- **Focused study on limited PFAS** – Very few PFAS have been rigorously evaluated for and have expert consensus on their toxicity, including toxicokinetics, toxicodynamics, and modes-of-action, and the combined effects of various PFAS (e.g., synergism, additivity) are not well understood;
- **Resource limitations** – The traditional paradigm of evaluating and regulating chemicals on an individual basis is not tenable for the thousands of chemicals in this class (from

the perspective of resources, time, and the urgency posed by possibly prolonging exposures and health risks);

- **Expected similarities** – Many PFAS are expected to share similar target systems and health endpoints due to similar fundamental chemical properties;
- **Toxicity** – Adverse health effects for certain PFAS have been demonstrated at low levels of exposure, and several PFAS precursor chemicals can be metabolized in the body or degrade in the environment to form more toxic, intermediate chemicals that are already commonly regulated and restricted;
- **Persistence in the environment** – If future research indicates additional PFAS are toxic, the class's persistence means they do not readily degrade and are difficult and costly to remediate once they are released to the environment or are present in other exposure media; and,
- **Regrettable substitutions** – There is already a historical basis for regrettable substitutions within the class.

The literature suggests PFAS are broadly associated with both cancer and noncancer outcomes. The range of known or suspected health effects is vast and covers most major body systems. Although the nature and severity of health effects are expected to vary, the shared chemical properties fundamental to PFAS contribute to concerns about toxicity across the class.

Health effects associated with PFAS have been studied using a wide range of methods and in various research settings. The extensive evidence related to PFAS toxicity and health effects primarily relies on human epidemiology studies and traditional animal model toxicity studies. Epidemiologic studies provide observations that occur among real humans. These studies are often either among people with very high exposure levels (such as occupational settings and industrially exposed communities), or in general population settings where exposures reflect "typical" exposure levels. Therefore, epidemiology studies offer direct information about health effects in humans, although estimating historic exposure levels, duration, frequency, and routes of exposure can be challenging and add to uncertainty. On the other hand, animal toxicity studies offer the benefit of controlled, known exposure levels and can provide important insight on dose-response relationships, identification of possible target organ systems and endpoints to consider in humans, and information on life-stage susceptibility (e.g., prenatal, fetal, elderly). However, insights from animal models—which commonly include mice, rats, rabbits, and guinea pigs—may not translate directly to humans. Traditional animal model toxicity studies have been complicated by significant interspecies variation in PFAS absorption, distribution, metabolism, and excretion (ADME), which hinders the direct translation of PFAS animal toxicity studies for human relevancy (ATSDR, 2021). Despite these challenges, human studies and animal toxicity studies are often consistent with respect to commonly affected organ systems in the body.

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- **PFAS Replacements.** Short-chain PFAS replacements were previously thought to present a lower likelihood of bioaccumulation and toxicity compared to their long-chain legacy counterparts, such as PFOA and PFOS. However, after their introduction and widespread use, research indicated that several replacement PFAS can exhibit similar toxic properties and are associated with similar health outcomes and target organ effects as long-chain PFAS (Gomis et al., 2018; Wang et al., 2015; U.S. EPA, 2021a; U.S. EPA, 2021b). As such, several short-chain replacements have already been regulated by key authoritative bodies. For example, the short-chain alternatives HFPO-DA (commonly known as GenX) and PFBS are both listed on the Candidate List of SVHC by REACH and have also been proposed for regulation in drinking water by U.S. EPA, on the basis of toxicity evaluations by their respective bodies (ECHA, 2019a; ECHA, 2019b; U.S. EPA, 2021a; U.S. EPA, 2021b).
- **Mechanistic Evidence.** Understanding the underlying mechanisms of PFAS toxicity is still in development, particularly for humans. The following sections will not focus on the mechanistic evidence for PFAS toxicity, because this is well summarized elsewhere (ATSDR, 2021; U.S. EPA, 2023d; U.S. EPA, 2023e). Briefly, the mechanistic evidence suggests activation of peroxisome proliferator-activated receptor-α (PPARα) may play a role in some PFAS-associated endpoints observed in both animal models and humans (National Toxicology Program [NTP], 2022a; NTP, 2022b). The role of PPARα may also explain some of the observed interspecies variation in PFAS toxicity (ATSDR, 2021; U.S. EPA, 2023d; U.S. EPA, 2023e), because many common laboratory models, such as rats and mice, are significantly more sensitive to PPARα agonists, as compared to humans. However, laboratory studies have also demonstrated mechanisms of several PFAS-associated endpoints that are not related to PPARα activation, and may involve oxidative stress, mitochondrial dysfunction, and activation of other nuclear receptors (ATSDR, 2021; U.S. EPA, 2023d; U.S. EPA, 2023e; World Health Organization, 2016; NTP, 2022b).

Absorption, Distribution, Metabolism, and Excretion

Absorption. PFAS can be absorbed into the body through oral, inhalation, and dermal routes, leading to numerous exposure scenarios and relevant exposure matrices, such as ingested substances (e.g., food and drinking water, ingested dust), inhaled media (e.g., dust, aerosols), and matrices that come into contact with the skin (e.g., clothing, carpeting, furniture). PFAS are also readily transferred from the pregnant and birthing parent to fetuses and infants via the placenta (i.e., in utero exposure) and breastmilk (i.e., lactational exposure), respectively. Oral exposure is the primary pathway of concern. Although the relative importance of different PFAS exposure routes can vary within the general population and between different PFAS, pharmacokinetic modeling and modeling of relative source contributions generally agree that food is the primary source of PFAS exposure for most human adults, followed by drinking water and dust and indoor air to lesser extents (Poothong et al., 2020; De Silva et al., 2021; Trudel et al., 2008; Haug et al., 2011; Vestergren & Cousins, 2009; Vestergren et al., 2012). Several studies predict that dust ingestion and indoor air inhalation can act as important exposure sources for some individuals (DeLuca et al., 2022; Haug et al., 2011). For breast-fed infants,breast milk is the primary exposure route (Mogensen et al., 2015; Papadopoulou et al., 2016), and hand-to-mouth activities, crawling, and dust ingestion are thought to be important secondary routes of exposure (Shoeib et al., 2011; Mogensen et al., 2015; Papadopoulou et al., 2016). See **Section 4.4.2** for more information on exposure scenarios.

As briefly mentioned above, **oral exposure** is the primary exposure route for the general population, and summarized evidence shows PFAS is rapidly absorbed through the gastrointestinal tract and remains bioavailable (ATSDR, 2021). PFAS-contaminated food, drinking water, and other beverages are the most likely sources of oral exposure in humans (see **Section 4.4.2**). Bioavailability may also be influenced by diet, with high fat diets associated with lower absorption rates for some PFAS (Li et al., 2015). The ingestion of PFAS-containing dust or aerosols also contribute to oral exposures.

Although PFAS can be absorbed through **inhalation** (ATSDR, 2021), studies of inhalation exposure are limited in humans, with the exception of exposure in occupational settings (e.g., fluorochemical manufacturers).

PFAS can readily penetrate human skin (Franko et al., 2012); however, existing research suggests **dermal** PFAS exposure is a less biologically relevant route and likely contributes minimally to internal body burdens for the average adult human (ATSDR, 2021; Franko et al., 2012; Ragnarsdottir et al., 2022). It should be noted that many studies rely on exposure estimates from hand-wipe studies and could be underestimating dermal absorption via larger surface area exposures (e.g., direct skin contact with large pieces of clothing). Preliminary research also suggests biological fluids, such as sweat and saliva, can facilitate dermal absorption of PFAS (Commission for Environmental Cooperation, 2017). Dermal absorption of PFAS is further dependent on physiochemical properties (e.g., PFAS ionization state), so the pH of a PFAS-containing product or the pH of the skin surface can also influence absorption rates. Notably, not all skin surfaces are uniformly susceptible to PFAS absorption, and characteristics such as skin thickness and structure, the condition and hydration of the skin, the presence of damage or injury, and the amount of hair coverage can all influence dermal uptake (U.S. EPA, 1992). More research is particularly needed on dermal PFAS absorption in or around potentially susceptible regions (e.g., eyes, lips, genitalia) and on the role of mucosal membranes in dermal PFAS absorption. These data gaps may be particularly important given that numerous PFAS-containing products, such as clothing, cosmetics, dental products, personal hygiene products, and menstruation products may contact potentially susceptible areas of the body.

- **ADME** is an abbreviation for the collection of processes that describes how a chemical enters the body (**a**bsorption), moves around the body (**d**istribution), changes within the body (**m**etabolism), and eventually leaves the body (**e**xcretion).
- **Absorption:** PFAS readily enter the body through the mouth, such as eating and drinking contaminated food and beverages. PFAS can also enter the body through breathing and through the skin, although to a lesser extent. More research is needed to understand how humans absorb PFAS.
- **Distribution**: PFAS move throughout the body via the bloodstream, which introduces PFAS into organs and tissues where they can then do damage. PFAS can accumulate in protein-rich tissues, such as the liver, kidneys, and lungs.
- **Metabolism:** PFAS are not easily broken down in the body due to their strong chemical bonds and resistance to degradation. This can lead to bioaccumulation in the human body.
- **Excretion:** PFAS can remain in the body for days to years, before leaving through urine, feces, and other excretion pathways. The length of time a PFAS chemical stays in the body before it is excreted largely depends on its chain length.

Distribution. After absorption into the bloodstream, PFAS are primarily found within the serum and plasma fractions of blood rather than the cellular fraction of blood (ATSDR, 2021; Jian et al., 2018). Notably, most common PFAS, including short-chain replacements, readily bind to proteins like serum albumin, which allows PFAS to be widely distributed throughout the body (Alesioet al., 2022; Allendorfet al., 2019; Beesoon & Martin 2015; Forsthuber et al., 2020). Studies of human cadavers have found PFAS in nearly every tissue, although the distribution of specific PFAS in the body may vary by chemical (Pérez et al., 2013).

In general, PFAS tend to be stored and accumulate in the blood and protein-rich tissues, such as the liver, kidneys, and lungs (ATSDR, 2021; Jian et al., 2018; Pérez et al., 2013). PFAS can also be found in cord blood, the placenta, and breast milk, contributing to key exposure pathways during early-life (Bangmaet al., 2020; Chen et al., 2017; Jian et al., 2018). PFAS can also cross the blood-brain barrier, although accumulation in brain tissue is highly dependent on the specific PFAS (Cao & Ng, 2021).

Metabolism. The carbon-fluorine bonds that make PFAS highly resistant to degradation in the environment also make PFAS resistant to metabolism in the body. Therefore, unaltered, parent PFAS compounds are typically the chemicals of concern for toxicity. However, there is also strong evidence for indirect exposure to certain PFAS through the metabolism and biotransformation of precursor chemicals; in particular, FTOHs, such as 8:2 FTOH, can biotransform to more toxic PFAS (e.g., PFOA), and can therefore contribute to the overall body burden of specific PFAS of concern (Butt et al., 2014; D'Eon & Mabury, 2007; D'Eon & Mabury, 2011).

Excretion. Given that most PFAS are not metabolized in the body, chemical clearance is primarily controlled by excretion. Half-lives of PFAS vary based on chemical structure: short-chain PFAS (e.g., PFBA, PFBS, PFHxA) typically have half-lives on the order of days, whereas long-chain PFAS (e.g., PFOA, PFOS, PFNA, PFDA, PFHxS) typically have half-lives on the order of years. Long-chain PFAS are particularly biopersistent due to their tendency to get reabsorbed by the kidneys and liver (ATSDR, 2021; Cao et al., 2022). Reabsorption can result in prolonged toxicity in the body and can contribute to bioaccumulation in an individual over time.

In humans, urinary excretion is the primary elimination route, and fecal excretion is an important secondary elimination route. There are distinct sex and age differences in elimination kinetics, with females typically eliminating PFAS more rapidly than males. Age and sex differences are thought to be partly related to different elimination pathways and differences in PFAS reabsorption by the kidneys and liver. Menstruation, pregnancy, and lactation can serve as secondary elimination routes in females and can lead to faster PFAS elimination than in their male or post-menopausal counterparts. Some estimates suggest menstruation could account for more than 30% of the difference in elimination observed between biological females and males (Wong et al., 2014). The additional excretion pathways available in reproductive-age females can also have important implications for PFAS exposure among fetuses and infants (see **Section 4.4.2**).

PFAS elimination rates are highly variable between species, with PFAS in humans exhibiting much longer half-lives (in the order of years) than in nonhuman primates and other mammalian models (in days or hours) (ATSDR, 2021). The uncertainty and variability in elimination rates contributes to the challenge of interpreting animal toxicity data for human relevancy.

Summary of Health Outcomes Associated with PFAS

Throughout the literature, PFAS exposure is frequently associated with numerous cancer and noncancer outcomes. However, study design, study quality, assessed PFAS compounds, confounder assessment, relationship consistency, effect sizes, and information about exposure levels and sources vary considerably in the primary literature. As noted previously, the most abundant sources of evidence for understanding the relationships between PFAS and health effects include epidemiologic studies and animal toxicity studies. These two key evidence streams provide distinct but complementary information, which can be considered together to strengthen our overall understanding of PFAS and health outcomes. These two primary evidence streams are also complemented by mechanistic studies and emerging research in computational modeling (e.g., pharmacokinetic modeling, quantitative structure-activity relationship modeling).

Given the complexity and variation in the primary evidence base, it is helpful to review documentation developed by authoritative bodies, which frequently review, critically evaluate, and integrate various streams of primary evidence and convene panels of experts to consider the evidence and draw conclusions. Numerous authoritative bodies have conducted reviews of the PFAS and health effects evidence to support regulatory and policy decision-making. These authoritative bodies typically use weight-of evidence or strength-of-evidence approaches to critically evaluate the evidence. Taken together, the conclusions from authoritative sources provide clearer insight into the strongest exposure-outcome relationships established by the literature to date.

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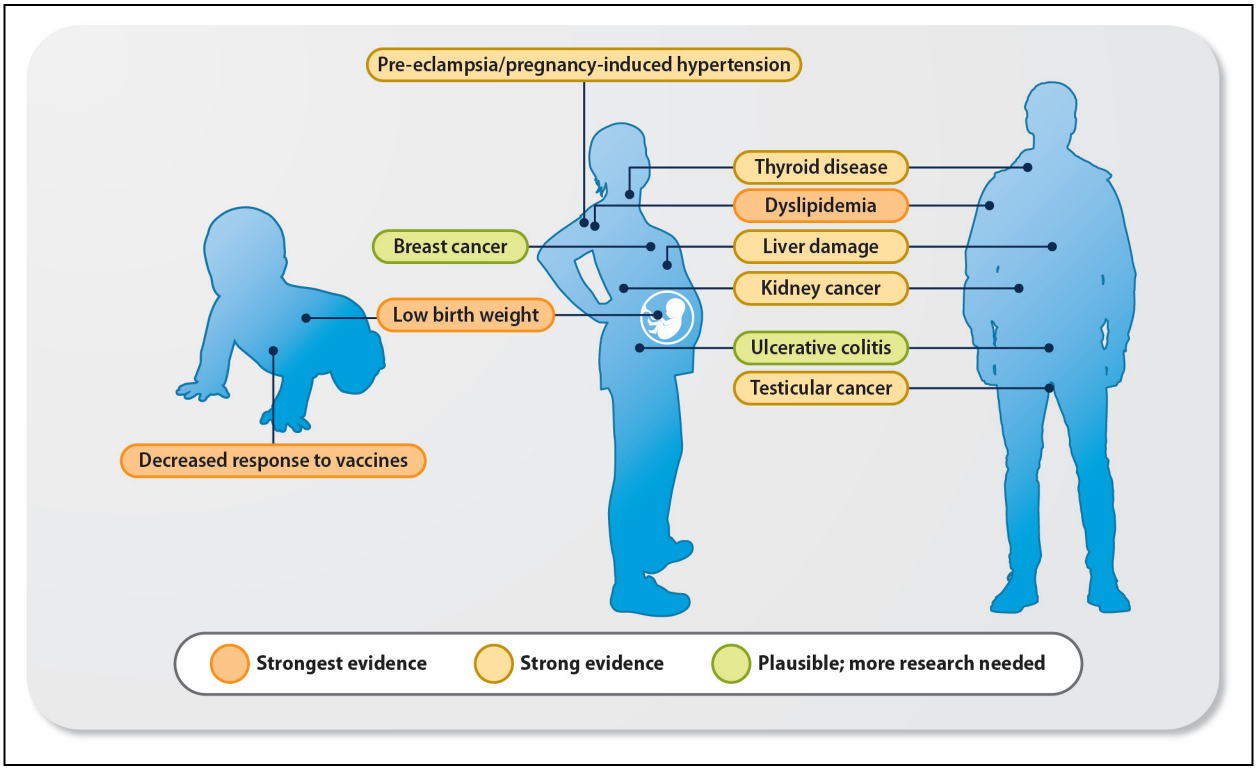
Adverse health effects observed following exposure to PFAS in rodent models and humans are very similar. This level of agreement between laboratory studies and epidemiological observations increases our confidence that these adverse health effects are strongly linked to PFAS exposures.

This is also an active topic, with numerous landmark reviews of health hazards being published, updated, or under review as of early- to mid-2023. Most authoritative sources acknowledge the significant challenge of the rapidly growing evidence base and the importance of continued research and critical reviews—many potential health outcomes currently without sufficient evidence may eventually bear out stronger or more conclusive weight-of-evidence ratings over time.

This section provides an initial overview of key health outcomes commonly associated with PFAS across the class of chemicals. This narrative summary is primarily based on several recent reviews conducted by authoritative bodies and is further illustrated in **Figure 4-26**. Given that PFOA and PFOS are among the primary compounds evaluated in the health literature to date, a more detailed profile on key toxicity information for those chemicals are provided briefly below and in more detail in **Appendix E**. Finally, several other common PFAS of note are briefly highlighted below.

Figure 4-26. Summary of Key Human Health Outcomes Recognized or Suspected to be Associated with PFAS Exposure



Notes: **Strongest evidence:** Multiple authoritative bodies have concluded there is an association between at least one PFAS chemical and this health outcome. **Strong evidence:** an authoritative body has concluded there is an association between at least one PFAS chemical and this outcome, or multiple authoritative bodies have identified there is suggestive evidence for an association. **Plausible; more research needed:** evidence for an association between a PFAS chemical and this outcome is common in the primary literature, and/or authoritative bodies have identified this as a health outcome for further research. The primary authoritative sources used for this figure—and summarized in the following sections—are several U.S. EPA documents, Agency for Toxic Substances and Disease Registry's (ATSDR's) 2021 Toxicological Profile on PFAS, EFSA's 2020 Panel on Contaminants in the Food Chain Report, the National Academies of Science, Engineering and Medicine's (NASEM's) 2022 Guidance document, the National Toxicology Program's (NTP's) Monograph on Immunotoxicity for PFOA and PFOS, and IARC's Monograph including PFOA. See **Appendix D**, Tier 1 Evidence Results for more details.

Cancer Outcomes. Various types of cancer are of particular interest for PFAS research, in part due to the frequency and wide range of cancers associated with PFAS exposure in animal model studies (NTP, 2020; World Health Organization, 2016). Data related to the underlying mechanisms of PFAS carcinogenicity vary with respect to availability and translatability to humans (ATSDR, 2021). Epidemiological evidence for associations between PFAS and cancer in humans can be found throughout the primary literature, although evidence is often strongest in highly exposed populations, such as occupational cohorts and communities with known contamination or exposure sources. Authoritative bodies have also generally focused their critical reviews of cancer risk on PFOA and PFOS exposure in humans, leading to less complete evidence bases for other PFAS. Key highlights related to PFOA and PFOS carcinogenicity include information from the following organizations:

EUROPEAN ACADEMIC FOCUSED ON PFAS

There is still much that we don't know about the long-term effects of PFAS on people, however what we do know shows that PFAS should be completely phased out.

RETAIL PACKAGING INDUSTRY VETERAN

There is a consensus among industry peers that PFAS has significant negative impacts on human health.

- IARC classified PFOA as "possibly carcinogenic to humans" (classification 2B) in 2017, on the basis of *limited* evidence for kidney and testicular cancer in humans; this conclusion was primarily supported by epidemiological evidence from occupationally exposed persons (World Health Organization, 2016).
- In 2023, U.S. EPA similarly concluded PFOA is "likely to be carcinogenic to humans," also citing kidney and testicular cancer observed in humans (U.S. EPA, 2023d; U.S. EPA, 2023f).
- Other prominent authoritative bodies have identified PFOA as carcinogenic or associated with cancer outcomes, including the NTP, ATSDR, and NASEM (NTP, 2020; ATSDR, 2021; NASEM, 2022).
- PFOA is also listed in California's Proposition 65 list in part due to its carcinogenicity.
- Although the cancer-related evidence is less developed for PFOS as compared to PFOA, U.S. EPA concluded PFOS is "likely to be carcinogenic to humans," primarily on the basis of liver tumor findings in animal studies that were deemed relevant to human health (U.S. EPA, 2023e; U.S. EPA, 2023h).
- IARC plans to update and newly rate the carcinogenicity of PFOA and PFOS, respectively, in late 2023 (World Health Organization, 2023). See **Appendix F** for additional information on PFOA and PFOS and cancer.

The carcinogenicity of other specific PFAS is beginning to be assessed. U.S. EPA recently concluded there is *suggestive* evidence that the short-chain replacement GenX chemicals (HFPO-DA) are carcinogenic to humans (U.S. EPA, 2021a).

Beyond testicular and kidney cancer, for which there is the strongest evidence in humans, other types of cancer have been proposed in the literature. However, the evidence is mixed or inconclusive for humans to date, including for breast cancer, ovarian cancer, endometrial cancer, bladder cancer, liver cancer, prostate cancer, non-Hodgkin's lymphoma, and thyroid cancer (Steenland & Winquist, 2021; U.S. EPA, 2023d; U.S. EPA, 2023e; U.S. EPA, 2023g; U.S. EPA, 2023h).

Noncancer Outcomes. Although health endpoints and target systems can vary depending on the specific PFAS chemical, the class is broadly associated with adverse effects in the immune system, disturbances in lipid metabolism, adverse effects in the liver, thyroid hormone disruption, and developmental and reproductive toxicity. Numerous other adverse health effects are suspected to be associated with PFAS, and research related to health effects and toxicity continues to be published and evaluated at a rapid rate.

As discussed previously, many decision-makers are exploring multi-chemical or class-based approaches for analyses and regulation. Notably, multi-chemical or class-based evidence reviews have recently been conducted by several authoritative governmental and nongovernmental sources, including the U.S. EPA, NASEM, ATSDR, and EFSA.[8]

These reviews provide excellent and reputable syntheses of the evidence base related to key health effects found in primary studies across the PFAS literature. Highly authoritative sources have concluded there is sufficient evidence to establish a relationship between PFAS and the following major systems:

- Immunotoxicity, including decreased antibody response to vaccines (EFSA, ATSDR, NASEM, EPA);
- Cardiometabolic toxicity, including dyslipidemia and increased total cholesterol (EFSA, ATSDR, NASEM, EPA); and
- Developmental toxicity, including fetal and/or infant growth outcomes (EFSA, ATSDR, NASEM).

Authoritative sources have drawn varying conclusions on the strength-of-evidence for several other commonly reported noncancer outcomes. However, multiple authoritative sources have generally concluded there is *at least* suggestive or limited evidence related to PFAS exposure and the following major outcomes:

- Immunotoxicity, including autoimmune outcomes like ulcerative colitis, increased risk of respiratory infections, and increased risk of asthma- and allergy-related outcomes;
- Hepatotoxicity, including increased alanine aminotransferase (ALT) and decreased serum bilirubin levels;
- Endocrine disruption, including alteration in various thyroid hormones; and
- Reproductive toxicity, including hypertensive disorders of pregnancy.

A wide variety of noncancer health effects have been proposed in the literature; however, the evidence is mixed or inconclusive to date, including for impacts related to insulin dysregulation and diabetes, obesity and altered metabolism, attention-deficit/hyperactivity disorder, autism spectrum disorder, menstrual cycle length, gestational term length, fertility, osteoarthritis, and kidney function and disease (Fenton et al., 2021; ATSDR, 2021).

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- It is clear that PFAS exposure perturbs the physiology of living organisms, leading to adverse health effects. We don't need to know the specific molecular mechanisms behind PFAS toxicity to understand that their exposure can increase the risk of these adverse health effects.
- "Intert" is a term often used to describe some PFAS because they are not chemically reactive. However, many of the PFAS studied are "interactive" with all sorts of biomolecules, which is why their exposure can increase the risk of chronic diseases.

Chemical and Health Summary: PFOA and PFOS

Given that PFOA and PFOS are the primary PFAS evaluated in the health literature and are among the PFAS of focus for decision-makers (due to both ubiquity, ecological and biological persistence, severity of health effects, and health effects found in

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[8] As of mid-2023, the European Chemicals Agency is considering a class-based restriction of PFAS and has broadly considered PFAS toxicity and human health hazards; however, this resource is still considered draft as of the date of this white paper and cannot yet be cited.

susceptible populations), a more detailed profile on key toxicity information for those chemicals are provided in **Appendix F**. A summary of key noncancer endpoints observed in humans is provided in **Table 4-13.**

Table 4-13. Summary of Key Noncancer Health Effects Associated with PFOA and PFOS Exposure in Humans and Evaluated by Authoritative Bodies

Outcome	Key Noncancer Endpoints Observed in Humans	Weight-of-Evidence Assessment [a]
Hepatotoxicity	Increased ALT levels (PFOA and PFOS)	Moderate evidence in humans
Immunotoxicity	Decreased childhood antibody responses (PFOA and PFOS)	Moderate evidence in humans [b]
Cardiometabolic toxicity	Altered serum lipids (PFOA and PFOS)	Moderate evidence in humans
Developmental toxicity	Fetal growth restriction (PFOA and PFOS)	Moderate evidence in humans
Reproductive toxicity	Changes in testosterone levels and sperm parameters in males (PFOA) Preeclampsia and gestational hypertension in females (PFOA)	Suggestive, but not indicative evidence in humans
Endocrine disruption	Changes in thyroxine levels in children (PFOA) Thyroid disease in adults (PFOS) Disruption to thyroid stimulating hormone in children (PFOS)	Suggestive, but not indicative evidence in humans
Neurotoxicity	Attention-deficit/hyperactivity disorder and autism spectrum disorder and autistic behaviors (PFOS)	Suggestive, but not indicative evidence in humans

[a] Weight-of-evidence assessments are from EPA's corresponding maximum contaminant level goal (MCLG) documents, unless otherwise noted (U.S. EPA, 2023d; U.S. EPA, 2023e).

[b] Weight-of-evidence assessment is from EPA's corresponding MCLG documents and NTP's Monograph on Immunotoxicity (NTP, 2016; U.S. EPA, 2023d; U.S. EPA, 2023e).

As discussed above, PFOA and PFOS are both considered likely carcinogenic to humans, with testicular and kidney cancers demonstrating the strongest evidence in humans (U.S. EPA, 2023d; U.S. EPA, 2023e; NASEM, 2022; World Health Organization, 2016).

Chemical and Health Summary: GenX, PFBS, PFHxS, PFNA, and PFDA

Although PFOA and PFOS are the primary PFAS evaluated in the health literature, the evidence advances each year for other PFAS chemicals and their potential associations with health effects in humans. Evidence for adverse outcomes is associated with a variety of PFAS chemicals, including legacy PFAS and short-chain replacements, which were originally intended to pose less risk for toxicity. Health effects summaries are presented below for five chemicals that are commonly found in the toxicity literature and have active or pending regulatory considerations.

GenX. GenX chemicals (HFPO-DA and its ammonium salts) are short-chain PFAS intended to replace PFOA, a toxic, long-chain, legacy PFAS. However, similar health outcomes have been observed between the chemicals. In reviewing the toxicity literature, U.S. EPA concluded there is evidence of a range of effects related to hepatotoxicity, developmental toxicity, immunotoxicity, and hematology, and further concluded there is suggestive evidence that GenX is carcinogenic to humans (U.S. EPA, 2022c). GenX chemicals were proposed for regulation in drinking water by EPA in early 2023 given the associated health effects (U.S. EPA, 2023i). GenX chemicals have been identified as SVHC by REACH and were found to have an equivalent level of concern as other substances identified as carcinogenic, mutagenic, and reprotoxic; persistent, bioaccumulative, and toxic (PBT); and very persistent and very bioaccumulative (vPvB) (ECHA, 2019-c). Although GenX chemicals have shorter half-lives than the legacy chemical they replaced, animal toxicity studies suggest adverse health outcomes can occur even at low doses of GenX exposure (U.S. EPA, 2021a). GenX may share similar modes-of-action as PFOA, and the liver and developmental outcomes still appear to be particularly sensitive to GenX exposure (U.S. EPA, 2021a; U.S. EPA, 2023i; Blake et al., 2020; U.S. EPA, 2022c).

PFBS. PFBS is a short-chain PFAS intended to replace PFOS, a long-chain legacy PFAS with known toxicity. U.S. EPA recently noted the small number of human studies available across the PFBS literature and identified most human evidence conclusions as equivocal overall (U.S. EPA, 2023i). However, there was sufficient animal toxicity evidence to support identifying PFBS as a hazard on the basis of thyroid effects, kidney effects, and developmental effects (U.S. EPA, 2021b); U.S. EPA concluded there was insufficient evidence to evaluate potential associations between PFBS and cancer outcomes. PFBS was proposed for regulation in drinking water by U.S. EPA in early 2023, given the associated noncancer health effects (U.S. EPA, 2023i). PFBS has been identified as a SVHC by REACH and was found to pose an equivalent level of concern as other substances identified as carcinogenic, mutagenic, and reprotoxic; PBT; and vPvB (ECHA, 2019-d). The thyroid appears to be particularly sensitive to PFBS exposure (U.S. EPA, 2021b).

PFHxS. Besides PFOA and PFOS, PFHxS and PFNA (discussed below) are the legacy PFAS that have the longest history of research attention and subsequent regulatory action. There is strong evidence supporting the classification of PFHxS as toxic and bioaccumulative. PFHxS has a half-life on the order of years in humans (ATSDR, 2021). It was identified as a SVHC by REACH on the basis of the chemical’s vPvB properties (ECHA, 2017). PFHxS was also recently listed as a Persistent Organic Pollutant by Stockholm Convention parties and was included in the food safety thresholds set by EFSA in 2020 (United Nations, 2022; United Nations, 2018; United Nations, 2019; EFSA Panel on Contaminants in the Food Chain, 2020). ATSDR (2021) concluded there are associations between human exposure to PFHxS and altered liver enzymes and decreased antibody response to vaccines, similar to other PFAS. Although data are sparser for humans, animal toxicity studies have demonstrated various endpoints related to hepatoxicity, developmental toxicity, and thyroid disease. U.S. EPA proposed PFHxS for regulation in drinking water in early 2023 on the basis of noncancer health effects, and generally agreed with—and heavily relied on—ATSDR’s conclusions to support the assessments underlying the proposed regulation (U.S. EPA, 2023i). Within the assessments to support proposed drinking water regulations, U.S. EPA concluded there was insufficient evidence to evaluate potential associations between PFHxS and cancer outcomes. U.S. EPA’s Integrated Risk Information System (IRIS) program is conducting a human health toxicity assessment for PFHxS (U.S. EPA, 2022e).

PFNA. A nine-carbon PFAS compound—has a half-life on the order of years in humans (ATSDR, 2021). ATSDR identified an association between PFNA exposure in humans and dyslipidemia. Although data are sparser for humans, animal toxicity studies have demonstrated various endpoints related to hepatoxicity, developmental toxicity, reproductive toxicity, and immunotoxicity (ATSDR, 2021). EFSA similarly concluded there was evidence for hepatoxicity and cardiometabolic disease, due to increased liver enzymes and increased total cholesterol levels, respectively (EFSA Panel on Contaminants in the Food Chain, 2020); PFNA was subsequently included in the food safety thresholds set by EFSA in 2020. PFNA was also listed as a SVHC by REACH on the basis of its reproductive toxicity and PBT properties (ECHA, 2015). U.S. EPA proposed PFNA for regulation in drinking water in early 2023 on the basis of noncancer health effects, and generally agreed with—and heavily relied on—ATSDR's conclusions to support the assessments underlying the proposed regulation (U.S. EPA, 2023i). Within the assessments to support drinking water regulations, U.S. EPA concluded there was insufficient evidence to evaluate potential associations between PFNA and cancer outcomes. EPA's IRIS program is conducting a human health toxicity assessment for PFNA (U.S. EPA, 2022f).

PFDA. A 10-carbon PFAS compound—has a half-life on the order of years in humans (ECHA, 2016). PFDA was identified as a SVHC by REACH on the basis of the chemical's reproductive toxicity and PBT properties (ECHA, 2016). ATSDR concluded there are associations between human exposure to PFDA and dyslipidemia and decreased antibody response to vaccines, similar to other PFAS (ATSDR, 2021). U.S. EPA's IRIS program is conducting a human health toxicity assessment for PFDA and recently published an external peer review draft in April 2023. Although this document is not final and was therefore not formally reviewed for this white paper, the preliminary draft indicates PFDA is likely associated with endpoints related to hepatoxicity, immunotoxicity, developmental toxicity, and reproductive toxicity (U.S. EPA, 2023j).

New Directions of PFAS and Health Research

Given the well-established relationship between PFAS and several immune system outcomes, recent research has focused on evaluating PFAS exposure in the context of the ongoing COVID-19 pandemic. Several studies have demonstrated slightly increased risk of COVID-19 infection associated with PFAS exposure, increased severity of COVID-19 infection, and increased risk of mortality from COVID-19 infection associated with PFAS exposure; however, none of the studies established a causal link (Ji et al., 2021; Nielsen et al., 2021; Grandjean et al., 2020; Catelan et al., 2021).

Advances in toxicology methods and analytical methods, including read-across approaches[9] and high-throughput analyses, are helping to address data gaps in this domain and advance the rate at which research is conducted. Recognizing the challenge posed by PFAS decision-making for any one agency, many government agencies are collaborating to identify and prioritize PFAS that pose human health risks. For example, U.S. EPA and NTP have created the Responsive Evaluation and Assessment of Chemical Toxicity program to develop read-across approaches. These types of programs could identify if toxicity information for data-rich substances—such as PFOA and PFOS—can translate to data-poor PFAS substances and to develop health-relevant grouping approaches. Computational modeling methods, such as pharmacokinetic modeling and quantitative structure-activity relationship modeling, are also further supporting research into critical data gaps within the class, including basic toxicity information about the many poorly characterized PFAS, the underlying physiochemical properties that determine PFAS behavior and mechanisms of toxicity in the body, and possible toxicological bases for grouping PFAS into subclasses or groups for risk management and regulation.

4.4.4 Available Human Health Risk Assessments

Human health risk assessments contextualize whether exposure to a chemical may present a risk. For instance, an acute exposure to a chemical at a low concentration may not present increased risk of health effects, whereas a chronic exposure to a chemical at a low concentration may present a concern. The assessments ultimately estimate the probability of adverse health effects among individuals who may be exposed to chemicals. The health effect

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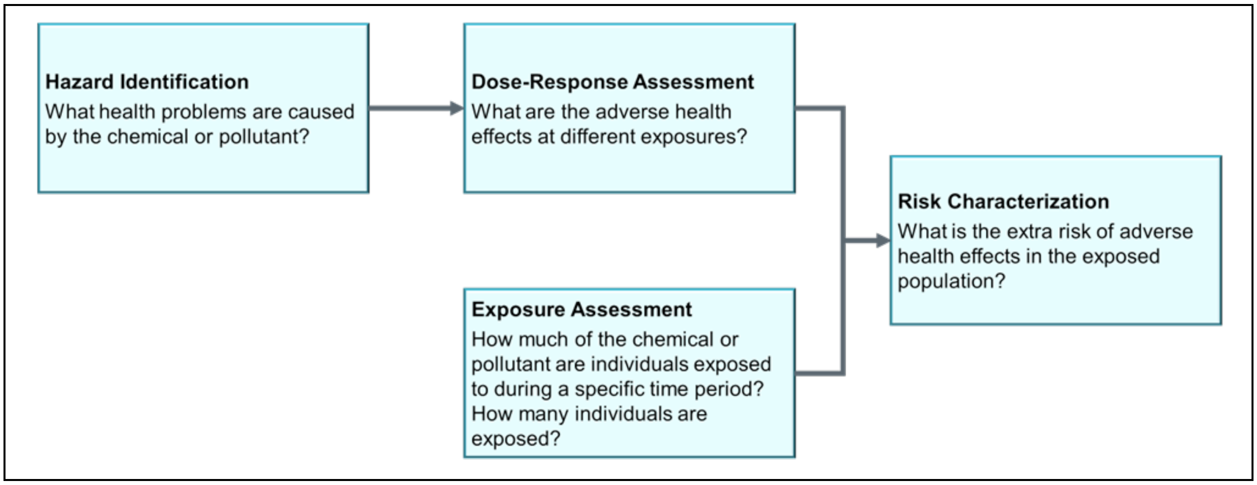
[9] Read-across methods predict information for one substance, such as endpoint information, using data of a similar substance.

of a risk assessment is always specified; the assessments may not be indicative of the risk to *all* health outcomes—assessments can focus on the risk of cancer health outcomes or noncancer health outcomes associated with chemical exposure. The U.S. EPA has defined four steps in the risk assessment process, which are described in **Figure 4-27**.

Figure 4-27. Steps of Risk Assessment Process



Source: U.S. EPA (U.S. EPA, 2022a).

As shown with each of the steps outlined above, there are different inputs required for risk assessments. Insufficient data at any of these steps limits the ability to perform a proper risk assessment. Therefore, only health system effects with strong weights-of-evidence are used for risk assessments.

ATSDR and U.S. EPA have developed dose-response assessments for PFAS with strong weights-of-evidence, including PFOS, PFOA, PFHxS, PFNA, PFHxA, PFBS, and GenX. In the development of dose-response assessments, points of departure are used in calculations and typically represent an animal study dose or human exposure level at which no adverse effects are seen, or the lowest dose or exposure level at which adverse effects begin to be observed. To account for variability and uncertainty, uncertainty factors are applied to points of departure to ultimately develop a reference dose (RfD) or reference concentration. Uncertainty factors cover several different reasons for variability and uncertainty, such as extrapolation of animal data to humans (interspecies uncertainty), extrapolation of subchronic data to chronic, and differences between individuals.

Oral RfDs are estimates of the **oral exposure** level for humans that does not result in appreciable risk of adverse health effects, whereas inhalation reference concentrations are estimates of the **inhalation exposure** level for humans that does not result in appreciable risk of adverse health effects. When combined with exposure information, RfDs and reference concentrations can be used in many types of risk assessment and policymaking activities.

The dose-response assessments and risk characterizations described below are limited to the most well-characterized PFAS and most well-characterized health outcomes. Therefore, PFDA, PFUnA, PFHpA, PFBS, PFBA, PFDoA, and PFOSA are not included; although the chemicals were summarized in ATSDR's *Toxicological Profile for Perfluoroalkyls*, there was insufficient data for the derivation of any risk levels (ATSDR, 2021).

PFOS

The U.S. EPA develops safe drinking water standards based on the current weight-of-evidence for candidate chemicals. In March 2023, EPA proposed National Primary Drinking Water Regulation for six PFAS, including PFOS, to establish legally enforceable levels in drinking water (i.e., maximum contaminant levels [MCLs]). Additionally, EPA announced the non-enforceable public health goal for drinking water (i.e., maximum contaminant level goals [MCLGs]). The MCLG is the maximum level of a contaminant in drinking water at which no known or anticipated adverse effect on the health of persons would occur. The MCL for PFOS has been proposed at 4.0 parts per trillion (ppt) and MCLG at 0 ppt.

Although the MCL and MCLG for PFOS are specific to drinking water, ATSDR has assessed whether there was sufficient data for several exposure durations and routes to develop minimal risk levels (MRLs). The MRLs are used as screening levels to determine whether environmental exposures are expected to result in adverse health effects. If the exposure is below the MRL, then an adverse health effect is *not* expected; conversely, if the exposure is above the MRL, then an adverse health effect may occur. An intermediate-duration oral MRL of 2×10^{-6} mg/kg/day was derived based on the critical effect of delayed eye opening and decreased body weight in the offspring of rats (ATSDR, 2021). However, acute-duration and chronic-duration oral were not derived due to insufficient data. Additionally, MRLs for all exposure durations (acute, intermediate, and chronic) for inhalation were not derived.

PFOA

In addition to the MCL and MCLG proposed for PFOS, the same were proposed by the U.S. EPA for PFOA at 4.0 ppt for the MCL and 0 ppt for the MCLG. Furthermore, similar to PFOS, ATSDR only derived an intermediate-duration oral MRL. An intermediate-duration oral MRL of 3×10^{-6} mg/kg/day was derived based on the critical effect of skeletal alterations in adult mice offspring (ATSDR, 2021).

In a pooled analysis of data from two studies—C8 Science Panel study and nested case-control study from the National Cancer Institute Prostate Lung, Colorectal and Ovarian Cancer Screening Trial—a lifetime excess risk for kidney cancer based on an exposure of 1 ng/mL (or 1 million ppt) from ages 20–80 was approximately 1.8 per thousand (with 95% confidence interval of 0.9–2.7) (Steenland et al., 2022). The lifetime excess risk reported by Steenland et al. (2022) is comparable to that reported by the California EPA (2.6 per thousand) (California Environmental Protection Agency, 2021).

PFHxS

An intermediate-duration oral MRL of 2×10^{-5} mg/kg/day was derived based on the critical effect of thyroid follicular epithelial hypertrophy/hyperplasia in adult male rats (ATSDR, 2021).

PFNA

An intermediate-duration oral MRL of 3×10^{-6} mg/kg/day was derived based on the critical effect of decreased body weight and developmental delays in the offspring of mice (ATSDR, 2021).

PFHxA

ATSDR determined that insufficient data were available for the derivation of any MRLs for PFHxA (ATSDR, 2021). The recently published IRIS Toxicological Review derived chronic and subchronic RfDs according to the weight-of-evidence associated with developmental, endocrine, hematopoietic, and hepatic effects described in **Section 4.4.3**.

Sum of PFAS

Typical PFAS risk assessments have targeted individual chemicals; however, there are also methods for calculating the risk for a mixture of chemicals, including hazard index, sum value, and relative potency factor approaches. Given individuals' exposure to several PFAS, EFSA used the sum value approach to perform a risk assessment on four PFAS: PFOS, PFOA, PFHxS, and PFNA. These four were selected based on concentrations observed in human blood, several similar health effects observed in animal models, and toxicokinetic models. A TWI of 4.4 ng/kg bodyweight per day was established for the sum of PFOS, PFOA, PFHxS, and PFNA (EFSA Panel on Contaminants in the Food Chain, 2020). Therefore, exceedances of the TWI indicate a health risk. It should be noted that the TWI accounts for infants as a susceptible population by considering infants' exposure via breastfeeding. Accordingly, "this TWI should prevent that mothers reach a body burden that results in levels in milk that would lead to serum levels in the infant associated with a decrease in vaccination response" (EFSA Panel on Contaminants in the Food Chain, 2020).

In characterizing risk, the Swedish Environmental Protection Agency calculated risk characterization ratios (RCRs) related to hepatoxicity and reproductive toxicity for 15 PFAS, wherein ratios were calculated using internal exposure levels (ng/mL serum) and the desired no-effect level (ng/mL serum) (Swedish Environmental Protection Agency, 2012). Separate analyses were conducted for the general population and occupationally exposed individuals, where occupational exposure focused on ski wax technicians. Specific data were used for four PFAS (PFHxS, PFOS, PFOA, and PFNA), and read-across methods were used for the remaining PFAS, which introduces some level of uncertainty when extrapolating toxicity data from one chemical to another. With respect to hepatoxicity and reproductive toxicity in the general population, RCRs for all PFAS were less than one, and therefore, these PFAS were not considered concerns for the general population. With respect to the occupationally exposed individuals, PFOA was considered a concern, with an individual RCR greater than one (3.8) (Swedish Environmental Protection Agency, 2012). Subsequently, cumulative exposure to the 15 PFAS assessed were also a concern among occupationally exposed individuals with RCR of ≤5.5. For reproductive toxicity, individual PFAS were not considered concerns; however, the RCR for cumulative exposure exceeded one.

The proposed U.S. EPA PFAS National Primary Drinking Water Regulation accounts for PFHxS, PFNA, GenX chemicals, and PFBS as a mixture. Rather than using MCL and MCLGs (like the approaches for PFOA and PFOS), a hazard index (HI) approach was used to establish health-based water concentrations (HBWCs) and a combined HI. For these four PFAS, the HBWCs were based on published reports of noncancer health effects associated with oral exposure. HBWCs for PFHxS and PFNA were both derived from the MRLs set by ATSDR, whereas GenX chemicals and PFBS were derived from the human health toxicity assessments published by the U.S. EPA (U.S. EPA, 2021a; U.S. EPA, 2021b; ATSDR, 2021). HBWCs are as follows: 9.0 ppt for PFHxS, 10 ppt for PFNA, 10 ppt for GenX chemicals, and 2,000 ppt for PFBS. The HI is then calculated by the sum of fractions for each PFAS; each fraction is the measured concentration divided by the HBWC. An HI greater than one indicates potential health risks from exposure to the chemical mixture.

Specific PFAS-Containing Products or Materials

Risk characterizations from the use of specific PFAS-containing products or materials appear to be limited. In risk assessment characterizations for different exposure pathways for children's textile products, the Danish EPA made calculations based on worst-case scenarios. For instance, for dermal absorption, the maximum parameters are for skin absorption and skin contact area. Dermal absorption and intake via saliva from an infant sleeping bag, rain jacket, or snowsuit did not result in potential risks of health significance; RCRs for both pathways were less than one (RCRs for dermal absorption were 0.0002–0.0011; RCRs for intake via saliva were 0.0002–0.001). Furthermore, the authors underscored that in a realistic scenario, only small portions of children's textiles products would be exposed to saliva (Danish EPA, 2015).

Exposure via indoor air accounted for the emission of PFAS to indoor air and release of PFAS during the entire life cycle of the product. The worst-case scenario, wherein the products were stored in kindergarten or school, resulted in significant daily uptake; however, the maximum RCR was still below one (RCRs were 0.07–0.36). Overall, the total uptake of PFAS released from a snowsuit (worn all day) among dermal absorption, oral exposure, and inhalation would result in an estimated RCR between 0.003 and 0.008. Lower estimated RCRs resulted from a child using an infant sleeping bag, mittens, or rainwear for part of the day. The Danish EPA concluded that children's direct exposure to PFAS from winter clothing results in negligible exposures to PFAS and low RCR values even when contributions are summed.

Additionally, the Danish EPA conducted risk assessments for cosmetic products (Danish EPA, 2018). Based upon the concentrations measured in cosmetic products described in **Section 4.1.1**, different dermal exposure scenarios were calculated. Dermal exposure scenarios considered how much of the product was applied daily, how much PFAS was in the finished product, dermal absorption of PFAS, and average human body weight. Based on two scenarios—one for PFAS in its acid form and one for PFAS in its salt form—the Danish EPA concluded cosmetic concealer has the highest estimated daily exposure for total PFAS at 2.96×10^{-5} mg/kg body weight per day. The authors underscored that after possible dermal absorption, chemicals can degrade in the body and release PFAS, and therefore, greater exposure to PFAS is possible than that measured in the products themselves.

4.4.5 Data Gaps, Limitations, and Uncertainties

Although there has been extensive research and syntheses on PFAS toxicity and human exposure, the data are still sparse for most PFAS. Given the thousands of chemicals that comprise the class of PFAS, obtaining sufficient exposure and toxicity data for each chemical is unfeasible with current research approaches. Although several experts have discussed the need to group PFAS for the purposes of assessing human health risk, experts disagree on criteria and methods for those groupings. Some experts have proposed groups based on the chemical structure classes, subclasses, and groups (shown in **Figure 2-2**), but others have proposed groups based on mode(s) of action, toxicokinetic properties, or types of adverse endpoints. Although it is clear that well-studied PFAS (e.g., PFOA and PFOS) pose health risks, there are inconsistent interpretations on which risks and at what exposure levels.

Even across the PFAS detailed in this section, there are limitations to research from the current state of science and technology. For instance, epidemiological studies often use a single, cross-sectional measurement of PFAS in biomatrices (such as serum); although those are validated biomarkers of relatively recent exposures, the levels in biomatrices cannot confirm historical exposures, and therefore may limit conclusions about causality between PFAS exposure and adverse health effects. This is particularly challenging for short-chain replacements, which are relatively rapidly cleared from the human body and are difficult to measure but are still suspected to be associated with adverse health outcomes. As described in **Section 2.1.4**, methods are still being developed and validated to analyze and quantify PFAS in biomatrices and environmental media; only 40 are included in the latest EPA method.

With much of the health effects research on general, highly environmentally exposed, and occupational populations, additional research is needed on different *susceptible* populations. Extensive research has investigated pregnant and lactating persons and their children, but other biological and exposure-related factors need to be addressed, including populations of certain disease statuses, nutrition statuses, and older life stage. Research into the potential health risks posed by PFAS across the lifetime is further challenged by the lack of epidemiological control groups, given that PFAS are detected in nearly all humans across the globe, and have been for the last several generations. Across all populations, the potential for toxicological interaction (e.g., additive or synergistic properties) is understudied. Research and regulation commonly address individual chemicals and their associated health effects, but this is not necessarily indicative of individuals' overall body burdens or health risks—individuals are routinely exposed to complex mixtures of PFAS through several exposure routes and sources.

5. Discussion

The class of PFAS is extensive with hundreds to tens of thousands of chemicals. Due to differences in definitions across stakeholders, this white paper compiled several PFAS lists that totaled 16,229 chemicals. Across objectives for this white paper, different PFAS were identified which are summarized in **Table 5-1**.

Table 5-1. Summary of PFAS Referenced throughout Source Characterization, Regulation, and Exposure and Human Health Risks

PFAS Category	Master List	Consumer Products	Industry	Policies and Regulations [a]	Exposure and Human Health Risks [b]
Perfluoroalkyl Substances	379	306	138	19	17
Polyfluoroalkyl Substances	450	384	167	1	9
Polymers	210	167	77	0	1
Undetermined	10	6	5	–	–
Not Categorized	15,180	–	–	10	56
Total	**16,229**	**863**	**387**	**30**	**83**

[a] The policies and regulations are largely focused on groups or subclasses of PFAS (i.e., long-chain perfluorocarboxylic acids) or the full class of PFAS.

[b] The PFAS summarized in this table for exposure and human health risks were based only on the chemicals referenced in the abstract of the literature described from the search strategies and subsequent screening. Many PFAS were not categorized because the chemicals did not overlap with the subset identified from consumer products and industry.

5.1 PFAS Sources in U.S. Consumer Products

PFAS Uses. PFAS have a large array of uses across industries and sectors to produce consumer and industrial products and other materials. Well-known applications of PFAS include providing nonstick properties to cookware and stain- and water resistance to textiles, including carpets, rugs, and outdoor apparel (e.g., rain jackets, rain boots). The application of PFAS is not restricted to general consumer products but also children's products, especially among children's clothing. The durability and performance of these products are desirable and expected by consumers.

Releases into the Environment. The lifecycle of PFAS and PFAS-containing products reveal that there are several points in which PFAS may be released for environmental and/or human exposure and subsequently downstream human health effects. Although the release of PFAS throughout product use is not as well-characterized, it is clear that PFAS and precursors can be released through the production of the chemicals themselves and PFAS-containing products. The facilities release PFAS through air emissions and industrial discharges, which contaminate the ambient air and sources of drinking water (e.g., groundwater, surface waters). Furthermore, all products eventually end up in the waste stream whether they are disposed of in a landfill, composted, recycled, or washed down the drain to a wastewater treatment plant or septic tank). Each of the waste streams result in the products potentially leaching or releasing PFAS into the air, biosolids and sewage sludge, sediment, soil, surface water, and groundwater. This is of particular concern for the agricultural operations used for crops and livestock as well as for the water sources used for drinking. Overall, given the high levels of historical and ongoing use of PFAS and their many functional uses, significant amounts of PFAS are common in the air, groundwater, surface water, and soils from production, use, and disposal. Currently, methods to identify and remediate PFAS contamination are costly; therefore, many entities have underscored the need for source controls and replacement of PFAS compounds in consumer products.

PFAS Labeling and Alternatives. Even among products labeled as “PFAS-free” or “PFOA/PFOS-free,” there are sometimes detectable levels of PFAS due to several potential factors including: contamination in facilities where other PFAS-containing products are manufactured; narrowly interpreting what chemicals are considered under the class of PFAS; and brand and/or generic names used by suppliers. Even if labeling and reporting requirements were more stringent, some experts have stated that given the environmental impact and safety concerns with PFAS-containing products, the responsibility should not rest with consumers deciphering labels, but rather with manufacturers using alternatives with low environmental impacts that are rigorously tested for safety. Additionally, testing for PFAS compounds is costly and is not conducted regularly.

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- Aside from PFAS, other chemicals have raised similar concerns in consumer products, including phthalates and BPA. Phthalates are often incorporated into the production of plastics for durability and/or pliability. The chemical and physical properties of phthalates make the chemicals useful for several different applications and products. Personal care products, plastic packaging, and vinyl flooring are examples of products where phthalates are used. In response to the health concerns regarding phthalates exposures via consumer products, the Consumer Product Safety Improvement Act of 2008 prohibited childcare articles and children’s toys containing concentrations of more than 0.1% of three types of phthalates.
- With concerns regarding BPA, many manufacturers substituted BPA with bisphenol S (BPS) and labeled those products as “BPA-free.” This aligns with the trends of PFAS; although PFOA and PFOS have been phased out of manufacturing in the United States and other countries and products are labeled as “PFOA/PFOS-free,” other PFAS take their places, leading to regrettable substitution, as another PFAS compound may have similar exposure and health concerns.

5.2 PFAS Commodity Market Trends

Production. In furthering assessing the role of PFAS in the market, it is difficult to identify PFAS production and use in the economy because PFAS commodities are not distinguished from other chemicals and reported data on PFAS volumes are scarce. Available data and the commodity classification system (i.e., NAICS) suggest that PFAS production occurs primarily within chemical manufacturing facilities and is directly used by chemical and other types of manufacturers before being sold embedded in products to other manufacturers or retailers. Domestic PFAS-producing and PFAS-releasing facilities are concentrated in the eastern part of the United States, spanning from the Gulf Coast to the upper Midwest to the Eastern Seaboard. Major points of PFAS handling and release risks include these production facilities, marine, air and land ports of entry, and direct users of PFAS throughout the United States.

Demand Projections. Approximately 3 billion pounds of PFAS are produced each year in the United States alone. If the fraction of domestic PFAS volume that is internationally traded is similar across major PFAS trading countries (e.g., China, Japan, Germany, India), global PFAS production could conservatively exceed 10 billion pounds per year. Available chemical reporting and market trends data suggest that PFAS production and use has most likely been flat to slightly declining over the past 10 years. Given relatively slow economic growth projected for the United States and the steady-to-declining production against the economic growth of the past 10 years, it appears unlikely that PFAS production will grow with the overall economy in the future unless we see new sources of demand either through expanded use cases or consumer populations (e.g., middle income countries with new demand for U.S. exports of PFAS or PFAS-containing products). To the contrary, increasing calls for regulation and identification of substitutes could potentially reduce PFAS production and demand. Still, the accumulated stock of historical PFAS production, continued production of goods with embedded PFAS, and environmental releases at 0.01%–0.02% of production per year will continue to present significant PFAS into the environment and associated human exposures into the foreseeable future.

5.3 PFAS Regulatory Trends and Alternatives

International Commitments. The regulatory landscape surrounding PFAS has increased rapidly over the last couple years because of increased knowledge of exposures and potential human health risks. The European Union and member states of the Stockholm Convention and Rotterdam Convention have made commitments to protect human health and the environment with goals to eliminate the use of PFOA and PFOS and several other PFAS under review. However, the United States is not a ratifying party in either convention. Most notably, five countries (Denmark, Germany, the Netherlands, Norway, and Sweden) submitted a proposal to ECHA that seeks to ban the production and use of PFAS as a class to reduce risks posed to the environment and humans. If approved, the restriction would be among the largest chemical bans.

Domestic Regulations. Conversely, federal regulations in the United States have focused on individual chemicals primarily in environmental media. Additionally, regulating PFAS one-by-one would be an arduous process. Without federal regulations, such as the proposal to ECHA, states have adopted and proposed policies to ban PFAS as a class in certain PFAS-containing consumer products, especially with respect to food packaging (e.g., disposal food containers from fast food chains) and textiles. The proposal to ECHA and certain state-level regulations avoid PFAS being replaced by another related and potentially regrettable substitution.

Regrettable substitution (once known as substitution whack-a-mole) is when a compound of unknown environmental fate replaces a known bad actor chemistry. Often regrettable substitution leads to a chemical associated with equal, or potentially greater, human health and environmental effects becoming a staple in products. Regrettable substitution has happened in the past when consumer outcry over a chemical was strong and pushed a company to immediate action or when regulation did not provide adequate time for a company to identify an effective and safe alternative.

Voluntary Phase-Outs. Although PFAS are extensively used in the manufacturing process and production of consumer and industrial products, there are some cases where companies voluntarily phase out individual chemicals or the whole class. The reasons for voluntary phase-out vary; some companies are committed to environmental sustainability, but others are preparing for pending regulations. For the former, ChemSec has a list of 108 companies and counting that have a strong dedication toward moving away from PFAS in products and supply chains since 2020 (ChemSec, n.d.). However, that is not necessarily a list of companies that have already researched and developed what alternatives will be used to replace PFAS in products and supply chains. For companies preparing for pending regulations, discussions with various types of industry in the value chain relayed a fear across several stakeholders that the different state-level regulations are not providing adequate time to identify, vet, and ensure the safety of alternatives. Current alternatives for certain applications already exist with minimal impact on perceived performance, whereas other applications may not be as easily replaced. Many companies still need to test alternatives within their manufacturing processes to determine which are feasible.

Stakeholder Collaboration. Stakeholders have noted that identifying viable alternatives is a collaboration and innovation problem. In Sweden, RISE is an independent, state-owned research institute that has developed a program, POPFREE, that works collaboratively with industry to develop alternatives. Collaborators at POPFREE have worked to identify alternatives for several industries who have paid into the program for support (POPFREE, n.d.). For the 16,229 PFAS identified for this white paper, it is essential to look at each application and understand what role PFAS are playing in each product or product component. A substitute for one application often may not be viable for another application.

TECHNICAL CORNER

The concept implemented at POPFREE includes several steps:

- An initial search for alternatives using an innovation-based methodology called technology scouting to identify potential alternatives developed for other purposes and to understand if they can act as alternatives.
- If technology scouting does not yield a viable result, then the next step would be to proceed to the development of a novel alternative, as POPFREE has been doing with industry.
- Alternatives should be evaluated along with robust health, toxicology, and environmental testing that ensures that the alternative will not be the next chemical being evaluated for regulation due to potential exposure or health effects.
- In general, our discussions indicate that some companies using PFAS for products are willing to replace PFAS; however, companies producing PFAS are less willing. Knowing this is the case may provide opportunities to push companies to take responsibility for PFAS stewardship, work collaboratively to develop analytical standards and methods, and ensure better PFAS substitutions.

5.4 Potential Exposure and Human Health Risks

The characteristic persistence of PFAS leads to numerous concerns for human exposures and health effects. PFAS are highly mobile in the environment and do not readily break down in the environment or in our bodies. These properties mean they can enter and accumulate in many matrices relevant for human exposure. The ubiquity of PFAS-containing products in our everyday lives (e.g., homes, offices, childcare centers, vehicles, recreational settings) further contributes to daily exposures and the continued accumulation of PFAS in our bodies over time.

Given the ubiquity of PFAS in the environment, diet, and consumer products, there are several sources and pathways for humans to be exposed to PFAS. Ingestion of PFAS-contaminated drinking water and food is the primary exposure pathway for the general population. Additional research is needed on other exposure pathways, particularly for dermal absorption, such as direct contact with consumer products.

Even though the literature base is still developing, there is significant evidence pointing to PFAS exposure and a wide array of adverse health effects. Several PFAS are associated with various types of cancers in humans and animal studies. PFAS are also commonly associated with noncancer health outcomes in the liver, immune system, fetal and infant growth and development, and how our bodies regulate cholesterol. Given the range and severity of human health effects, many authoritative bodies around the globe are moving swiftly to regulate PFAS under their jurisdiction. Although some entities have focused on the long-chain, legacy PFAS, many others are moving to regulate or restrict PFAS groups or the class of chemicals in its entirety. This is driven in part by the precedent for regrettable substitutions within the field of toxicology—specifically the regrettable substitutions that have already occurred within the realm of PFAS. Several long-chain PFAS have already been regulated or voluntarily phased out of use based on health and environmental concerns, leading to the use of short-chain PFAS as replacements. These short-chain replacements, such as GenX and PFBS, were previously thought to pose less risk for toxicity and accumulation in humans and the environment. Unfortunately, evidence indicates there are health concerns associated with these replacements, even though they are cleared from the body more rapidly than their legacy counterparts. Although chemical structures and properties differ between individual PFAS, their shared features and properties mean certain health concerns may be inherent to this class of chemicals. Furthermore, adverse health effects can be found at very low levels of PFAS exposure, leading many authoritative bodies to set extremely low thresholds for regulatory action.

6. Uncertainties and Limitations

As described throughout this white paper, there are several data gaps, limitations, and uncertainties across each of the objectives. This white paper provides a scoping review of several topics related to PFAS in consumer products. As a scoping review, there are several limitations that should be noted. The literature searches and screening processes used aspects of a systematic protocol; however, a systematic protocol was not followed in its entirety. For instance, although literature searches were conducted, the synthesis of evidence for the white paper itself relied largely on reports published by authoritative entities with supplemental sources to close gaps or strengthen the evidence. Additionally, when developing the database and characterizing those results throughout the white paper, it was limited to already existing datasets and/or databases that could be readily downloaded or exports in a usable format (e.g., not PDF files); information from peer-reviewed literature and reports was not extracted to further develop our database. This white paper should not be perceived as a comprehensive account of the state of the science of PFAS.

Regarding the state of the current research and science, there are also several limitations. Firstly, the definition of PFAS is still not agreed upon by all stakeholders—academia, industry, regulators, and others (Andersonet al., 2022). As noted in **Section 2.1.2**, the reported definition for PFAS has been changed by the U.S. EPA. Although each of the sources used to compile the list of 16,229 chemicals were published by the U.S. EPA, there are differences in what is and is not considered a PFAS across offices. The list of chemicals used in this report should not be interpreted as a definitive list of PFAS published by the U.S. EPA. Other agencies have also adapted definitions; OECD changed the definition used in the last decade, and several other definitions have been used throughout the literature, which proves challenging from the regulatory and risk assessment perspectives (Andersonet al., 2022). Secondly, across the PFAS definitions used, the number of chemicals remain in the thousands, meaning much of the research on exposure, toxicity, and human health risk characterize only a small fraction. Analytical methods have not been developed and validated to quantify the exposure of an array of PFAS in biomatrices and environmental media. Although methods are developing rapidly, current analytical methods can only reliably detect and quantify around 40 PFAS in certain media. More sensitive methods are needed particularly when quantifying exposure to PFAS from children’s consumer products. For context, the third and fifth Unregulated Contaminant Drinking Water Monitoring Rule (UCMR3 and UCMR5) can be compared. For UCMR3, quantification of six PFAS in public drinking water between 2013 and 2015 used EPA Method 537 (Rev. 1.1). Minimum reporting levels ranged from 10,000 ppt to 90,000 ppt. For UCMR5, quantification of 29 PFAS in public drinking water between 2023 and 2025 uses EPA Method 533 with minimum reporting levels ranging from 2,000 ppt to 20,000 ppt. In one decade, the most sensitive minimum reporting level for PFAS improved by a factor of five.

Additionally, with respect to current analytical methods and research, consensus across stakeholders is needed on how to group PFAS for mixtures and subsequent risk assessments. Evidence is limited on cumulative exposure to several PFAS, which is more representative of everyday human exposure.

7. Next Steps

Although significant information exists in this white paper, next steps include additional 1) research, 2) regulation, and 3) consumer awareness of PFAS production, use in consumer products, occurrence in the environment, toxicity, exposure, and lifecycle.

Research. Notably, there are definitions that lack consensus across research, in addition to regulation both domestically and internationally. Consensus is needed on how PFAS are defined and which corresponding chemicals fall under that definition. Additionally, consensus is needed on the sensitivity of analytical methods used across industries to determine the presence of PFAS, whether it is a byproduct, contaminant, or intentional ingredient. Methods used by stakeholders such as those in academia and federal agencies, particularly NTAs, are often expensive and require extensive training that may not be feasible for industry. Consensus on definitions and methods will ultimately help with the awareness and communication of PFAS and PFAS-containing products and the adverse effects on the environment and human health.

Additionally, as research continues to be published, the new and existing data need to be synthesized to provide a comprehensive understanding of PFAS as it relates to consumer products and subsequent consumer exposure. OECD has underscored the need for publicly available and accessible information on the current production and use volumes of PFAS, especially polymeric PFAS (OECD, 2022). More expansive requirements for disclosure and reporting by industries along the supply chain are needed to better characterize the extent of both non-polymeric and polymeric PFAS at each stage of the lifecycle, as well as better characterize how PFAS is detected from unintentional addition. Although there are several reviews on exposure pathways, the largest focus in those reviews include ingestion of drinking water and ingestion of food. Dermal uptake experiments are needed to further understand RSC of PFAS (Ragnarsdottir et al., 2022). Furthermore, specific focus on consumer products is needed to understand the direct and indirect exposure to PFAS in those products.

Regulation. Although additional research is needed to further characterize PFAS occurrence in the environment, cumulative human exposure, toxicity for the broader class of PFAS compounds, and chronic health effects at an individual and population level – PFAS research to-date is sufficient to show that PFAS are deleterious to human health and commonly present in the environment from their production and use in consumer products along with their disposal. While some regulations are taking shape domestically and internationally to address PFAS concerns in the environment and in products, additional regulations are necessary to protect human health and the environment, provide consumers with products that are safe for use, and ensure that industry and product manufacturers have clear requirements so that they can appropriately substitute PFAS with safer alternatives that meet performance standards.

Consumer Awareness. As researchers further evaluate PFAS and regulators consider additional regulations, consumers can proactively learn more about PFAS and affect change by choosing to purchase products without potential PFAS in them. Not only will this reduce an individual's potential exposure, but on a larger scale it could help shift the consumer market by showing companies that PFAS-free products are desirable, leading to potentially lower usage and better labeling even in lieu of specific regulations. Without current labeling requirements, the key is to look for the product descriptions. Terms such as "waterproof," "nonstick," and "stainproof" are indicators that PFAS are likely present. Companies that voluntarily market a product as "PFAS-free" may in fact have substituted one better known PFAS for another PFAS compound. Consumer awareness could drive researchers, regulators, and companies to a common goal.

8. Conclusions

This white paper provides an overview of PFAS, particularly as PFAS relate to consumer products. PFAS are synthetic chemicals, ubiquitous in consumer products and the environment. Legacy chemicals—PFOA and PFOS—are studied extensively with exposure associated with adverse human health outcomes, including decreased response to vaccines, dyslipidemia, kidney cancer, and low birth weight. PFAS used as replacements for legacy chemicals (e.g., PFBS, PFDA, PFHxS, PFNA, and GenX chemicals) are less characterized but increasing in weights of evidence for associations with cancer and noncancer outcomes. The general population is primarily exposed via ingestion of PFAS-contaminated drinking water and food from its production and usage in consumer products, such as nonstick cookware and stain- and water-resistant apparel. Throughout the lifecycle of PFAS-containing products, there are several points of migration or release of PFAS or precursors into the environment, including through emissions from the manufacturing facilities, industrial discharge, and migration into landfills for municipal solid waste. As the domestic and international supply and demand continues for PFAS, and subsequently PFAS-containing products, these persistent chemicals will continue to contaminate the environments used for drinking water and food and the environments where individuals live and work. PFAS are a national concern and subject to current and proposed regulations. Reduction and, ultimately, elimination of PFAS use in consumer products and other applications would reduce human exposure and associated adverse health outcomes.

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