PFAS Exposure and Human Health Risk Management - A Policy Review

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This Master's Project

PFAS Exposure and Human Health Risk Management - A Policy Review

by

Callie Totaro

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Aviva Rossi, Ph.D.
# Table of Contents

*Abstract* ........................................................................................................................................... 5  

1. *Introduction* .................................................................................................................................. 6  

2. *Research Objectives* ..................................................................................................................... 8  

3. *Background* .................................................................................................................................. 9  

3.1. History of PFAS ............................................................................................................................ 9  

3.2. Grouping and Naming of PFAS ................................................................................................. 10  

3.3. Physical Characteristics of PFAS ............................................................................................... 11  

3.4. PFAS Uses and Sources of Release ........................................................................................... 12  

3.5. PFAS Life Cycle and Transport Through the Environment ......................................................... 14  

3.6. PFAS Uptake/Bioaccumulation ................................................................................................... 16  

4. *Human Health Risk Associations* ................................................................................................ 17  

4.1. Reproductive and Developmental Impacts ................................................................................. 17  

4.2. Organ Toxicity and Cancer Associations with PFAS ............................................................... 18  

4.3. At-Risk People Groups ............................................................................................................... 20  

4.3.1. Children and Pregnant Women ............................................................................................ 20  

4.3.2. Industrial Workers .................................................................................................................. 21  

4.3.3. Subsistence Fishers ............................................................................................................... 21  

5. *Regulatory Framework* ................................................................................................................. 22  

5.1. PFAS Production Bans .............................................................................................................. 22  

5.1.1. International PFAS Bans ....................................................................................................... 22  

5.1.2. United States PFAS Bans ...................................................................................................... 24  

5.1.3. Voluntary United States Phase Outs .................................................................................... 25  

5.2. PFAS Levels, Monitoring, and Reporting in the United States .................................................. 25  

5.2.1. Maximum Contaminant Levels ............................................................................................ 26  

5.2.2. Public Health Goals ................................................................................................................ 26  

5.2.3. Lifetime Health Advisories ................................................................................................... 26  

5.2.4. Notification Levels and Response Levels ............................................................................. 27  

5.2.5. Threshold Limit Values ......................................................................................................... 27  

6. *Methods* ...................................................................................................................................... 29  

6.1. Literature Synthesis, Tables, and Graphs ................................................................................... 29  

6.2. PFAS Consultant Interview and SWOT Analysis ....................................................................... 29  

7. *Results* ......................................................................................................................................... 30  

7.1. PFAS Sources and Exposure Routes ......................................................................................... 30  

7.2. SWOT Analysis and Discussion of Policy Approaches ............................................................. 35  

7.2.1. Whole Class PFAS Bans ........................................................................................................ 36  

7.2.2. Restricting PFAS Compound by Compound ........................................................................ 38  

7.2.3. Improving Health-based Screening Levels .......................................................................... 39  

8. *Discussion and Management Recommendations* ...................................................................... 40  

8.1. PFAS Source Control .................................................................................................................. 41
8.2. Enforceable Screening Levels and Monitoring ........................................ 42
8.3. Public Awareness ....................................................................................... 43
8.4. Summary of Management Recommendations ........................................ 44

9. Conclusion .................................................................................................... 46

10. References ................................................................................................... 47

List of Tables
Table 1 - Reported Cancer Cases
Table 2 - Literature Synthesis PFAS Sources and Exposure Pathways Results
Table 3 - Summary of SWOT Analysis

List of Figures
Figure 1 - PFAS Classes
Figure 2 - PFAS Chemical Makeup
Figure 3 - PFAS Cycle
Figure 4 - PFAS Human Exposure Map
Figure 5 - Time Weighted Average Exposure Example
Figure 6 - Literature Synthesis PFAS Source Results
Figure 7 - PFAS Exposure Conceptual Site Model

List of Acronyms
ADHD Attention Deficit Hyperactivity Disorder
AFFFs aqueous film-forming foams
APFO ammonium perfluorooctanoate
ATSDR Agency for Toxic Substances and Disease Registry
BMI Body Mass Index
BPA Bisphenol A
C Carbon
CDC Centers for Disease Control
C-F carbon fluorine bonds
C-H carbon hydrogen bonds
DOD Department of Defense
ECHA European Chemicals Agency
EFSA European Food Safety Authority
ERM Environmental Resources Management, Inc.
EtFOSA sulfuramid
F Fluorine
HDPE high-density polyethylene
HFPO-DA hexafluoropropylene oxide dimer acid
LHAs lifetime health advisories
MCLs Maximum Contaminant Levels
MCLGs  Maximum Contaminant Level Goals
NFPA  National Fire Protection Association
NHANES  National Health and Nutrition Examination Survey
NIEHS  National Institute of Environmental Health Sciences
NIOSH  The National Institute for Occupational Safety and Health
NLs  notification levels
NOAA  National Oceanic and Atmospheric Administration
NPDWR  National Primary Drinking Water Regulation
OECD  United Nations Organization of Economic Cooperation and Development
OEHHA  Office of Environmental Health and Hazard Assessment
ppt  parts per trillion
PFAS  perfluoroalkyl substances
PFBE  perfluorobutyl ethylene
PFBS  perfluorobutane sulfonic acid
PFCAs  perfluoroalkyl carboxylic acids
PFIB  perfluoroisobutylene
PFNO  perfluorononanoic acid
PFOA  perfluorooctanoic acid
PFOS  perfluorooctane sulfonic acid
PFHxS  perfluorohexane sulfonic acid
POP  Persistent Organic Pollutant
PHGs  Public Health Goals
RCRA  Resource Conservation and Recovery Act
RLs  response levels
SDWA  Safe Drinking Water Act
STEL  short-term exposure limit
SWOT  strength, weakness, opportunities, and threats
TRI  Toxic Releases Inventory
TSCA  Toxic Substances Control Act
TWA  time-weighted average
USEPA  United States Environmental Protection Agency
USFA  United States Fire Administration
USFDA  United States Food and Drug Administration
WWTPs  wastewater treatment plants
Abstract

For centuries, new chemicals and compounds have been invented to improve material longevity or make a product cheaper to produce. Throughout this time, emerging chemicals have often gone through inadequate testing that may not consider all long term environmental and human health effects before they have gone to market in the United States. As a result, thousands of harmful chemicals have ended up in the food supply, water sources, and everyday items of people in the United States with the negative health effects often not being discovered for decades after the start of circulation. By this point, removal and assessment of health impacts seem near impossible, especially for pervasive, bioaccumulative compounds. A relevant example of this problem is perfluoroalkyl substance (PFAS) which have been marketed to consumers since the 1940’s with adverse health outcomes not being acknowledged until the 1990’s. Some countries were quick to restrict PFAS production. However, the United States only began to implement restrictive policies and guidelines nearly 20 years after PFAS health studies started coming out. This study details adverse human health outcomes associated with PFAS exposure, identifies major exposure pathways and at-risk people groups, assesses current policies, and discusses whether current policies adequately address the exposure routes, along with suggested paths forward.

Results of this study identified industrial production and aqueous film-forming foams (AFFFs) as primary sources of PFAS release into the environment in the United States, along with other secondary sources. From the identified primary and secondary sources, this study demonstrates how PFAS travels through air, water, soil, and household products ultimately causing human exposure through ingestion, inhalation, and dermal contact. United States policy gaps identified in this study include lack of restriction on PFAS production and use, lack of enough enforceable screening levels that federally enforce concentration limits, and lack of warning labels on household items containing PFAS. Mitigative policy improvements in these areas are recommended for identified exposure route gaps to better protect human health, including suggested PFAS production and use bans, implementation of PFAS screening levels for more exposure routes, labeling of marketed PFAS items, and improved public education on PFAS exposure risks.
1. **Introduction**

Better profit margins, increased product longevity, and greater convenience have often been the motivation behind the invention of new chemicals (Cordner et al., 2021). These motivations and promises of economic relief have often superseded any risk evaluation of human and environmental health implications (Cordner et al., 2021). The first fully synthetic polymer was invented in 1869 in pursuit of a substitute for ivory as the popularity of billiards rose (Shah et al., 2021). From there, the first fully synthetic plastic was developed in 1907 in search of a substitute for shellac, an electrical insulator, to meet the growing electricity needs of a rapidly industrializing society (Shah et al., 2021). These inventions were the first of many that freed people from the economic limits of natural resource availability and began a perpetual reliance on synthetic materials.

As new materials and chemicals emerged, testing on environmental and human health impacts of circulation of these products was lacking (Smith, 1988). It was not until the passing of the Toxic Substances Control Act (TSCA) in 1976 that the United States Environmental Protection Agency (USEPA) started having some regulatory control over new chemicals being produced in the United States, with amendments being added in 2016 (Rayasam et al., 2022). However, there were several gaps and limitations in this original policy that left public health at risk, creating a public perception of the law being largely weak and ineffective (Krimsky, 2017). One of the main issues with the original TSCA was that it grandfathered in all chemicals produced before its implementation, assuming these chemicals were safe until proven to be harmful (Silbergeld et al., 2015; Wilson et al., 2009). Perfluoroalkyl substances (PFAS) were included in this pool of grandfathered chemicals and were allowed to remain in commerce without additional USEPA review (National Archives Federal Register, 2023). Original TSCA also placed the burden of proof in evaluating risk on USEPA instead of the manufacturer (REACH, 2006). With opportunity for political interference and limited authority to obtain necessary information to assess risk, few chemicals were actually regulated under the original TSCA (U.S. Government Accountability Office, 2013). Though there were 86,000 new chemicals registered for use between original TSCA implementation in 1976 and the 2016 TSCA amendments, only 10 of the new chemicals have been regulated by USEPA (U.S. Government
Accountability Office, 2013). Even substances like asbestos, a substance with known health risk and harm, slipped through the cracks of the original TSCA (Rayasam et al., 2022).

There were amendments made to the original TSCA in 2016 with the Frank Lautenberg Chemical Safety for the 21st Century Act (amended TSCA), now requiring USEPA to conduct risk evaluations of new chemicals and chemicals in commerce to determine if the chemical poses an unreasonable risk without economic considerations (The President’s Cancer Panel, 2010). If a chemical in commerce does present an unreasonable risk, USEPA is required to regulate the chemical to the extent necessary for that chemical to no longer present such a risk (Rayasam et al., 2022). PFAS are part of this class of chemicals in commerce that USEPA is now required to evaluate and regulate if deemed to pose an unreasonable risk to human health (National Archives Federal Register, 2024). However, there are still large gaps in the amended TSCA risk evaluation process. For instance, the USEPA risk evaluations limit exposure pathways considered under the TSCA and do not consider exposure pathways such as ambient air, disposal, or drinking water in their evaluations (Rayasam et al., 2022). Ultimately, this process systematically underestimates exposure and risk evaluations of new and existing chemicals in commerce, still leaving an active public health risk (Rayasam et al., 2022).

A look at the history of synthetic material development and the lack of surrounding regulation reveals a theme of United States chemical policies lagging behind emergence of health concerns and not being adequately protective of public health (Shah et al., 2021; Cordner et al., 2021). The ultimate result of this has been thousands of harmful chemicals ending up in the food supply, water sources, and everyday items of people in the United States with the negative health effects often not being discovered for decades after the start of circulation (Dean et al., 2020; USEPA, 1998). By this point, removal and assessment of health impacts seems near impossible, especially for pervasive, bioaccumulative compounds (Dean et al., 2020).

A relevant example of this problem is PFAS, as mentioned in discussion of the TSCA, which has been circulating to consumers since the 1940’s with adverse health outcomes not being acknowledged until the 1990’s and regulations not being implemented in the United States until the late 2000’s (Brennan et al., 2021; Gaines, 2022; USEPA, 1998). PFAS are considered ubiquitous forever chemicals, defined as chemicals that break down very slowly in the environment over hundreds or thousands of years (USEPA, 2023a). PFAS are considered one of the strongest compounds in organic chemistry because of their bond chemistry, particularly their
long chain carbon-fluorine tails composed of carbon-fluorine bonds (C-F bonds) which take long periods of time to break down (O’Hagan, 2007). PFAS are used in a variety of specialty and everyday items that most humans have encountered in their lifetime (Dean et al, 2020). This creates cause for concern about PFAS exposure pathways that still exist amidst developing regulations. Though there are thousands of different types of PFAS compounds, each with different potential pathways and impacts, with the exact number still being unknown, the focus of current regulations are the long-chain perfluoroalkyl carboxylic acids (PFCAs) (Brendel et al, 2018). PFCAs are a class of PFAS that have particularly dangerous human health and environmental effects because they take longer to break down in the human body and environment than other short-chain PFAS classes (Brendel et al, 2018; O’Hagan, 2007). Current debate centers around whether current United States policy adequately protects society from exposure to long-chain PFAS such as PFCA compounds and whether short-chain PFAS alternatives are actually safer (USEPA, 2018a). This study details adverse human health outcomes associated with PFAS exposure, identifies major exposure pathways and at-risk people groups, assesses current policies and whether these polices adequately addresses public health risk, along with areas for improvement. Mitigative policy improvements are recommended for identified exposure route gaps to better protect human health.

2. **Research Objectives**

This research synthesizes literature to identify PFAS sources, highlight major PFAS exposure pathways to humans, and target these sources and exposure pathways for mitigation through policy and best management practices. The risks associated with the emergence of PFAS and observed impacts to human health can be mitigated by addressing three main areas:

1) The largest sources of PFAS release into the environment

2) The human health risks associated with PFAS exposure and the major exposure pathways for humans

3) PFAS exposure pathway mitigations and current limitations to these mitigations

Findings show there are many adverse human health outcomes correlated with PFAS exposure through air, drinking water, and household products (OECD, 2002; Steenland et al., 2013; Saikat et al., 2013; Lopez-Espinoza et al., 2013; Barry et al., 2013). While the major exposure pathways responsible for these health risks can be mitigated through policy, current
policy is not addressing all PFAS exposure routes or life cycle stages (Rayasam et al., 2022; Brennan et al., 2021). This research improves upon current PFAS policies, making them more protective of human health by recommending further development of PFAS production bans, screening levels, and public awareness.

3. Background

3.1. History of PFAS

PFAS were invented in the 1930’s and became a staple in many household and industrial products in the 1940s and 1950s, starting with the commercialization of polytetrafluoroethylene (PFTE) by DuPont in 1946 for their non-stick cookware (Brennan et al., 2021; Gaines, 2022). Use of PFAS in these household and industrial products gained popularity due to the improved longevity, non-stick, and oil-resist nature of items made with PFAS materials (Brennan et al., 2021). Since their use became popular, their concentration in the environment and human blood serum has increased (CDC, 2017; NIEHS, 2023). This is problematic due to the perceived persistent, bioaccumulative, and toxic nature of some types of studied PFAS varieties, particularly long-chain PFAS varieties (OECD, 2002).

Study of the long-term environmental and health effects of these forever chemicals did not begin until the 1990s (USEPA, 1998). It was not until the early 2000s that any classification or regulations were passed globally, and these regulations were largely focused in Europe, not the United States (Brennan et al, 2021). In 2006, the USEPA invited several major manufacturers of PFAS to voluntarily phase out two PFAS types from their products through their Global Stewardship Program under the TSCA (USEPA, 2018b). Later in 2009, the USEPA released Provisional Health Advisories for PFOA and PFOS and in 2016 listed Lifetime Health Advisory Limits, defined as levels that are safe to consume over a lifetime without adverse health effects for these same compounds (USEPA, 2023c; USEPA 2016). However, these regulations and programs were largely passed as guidance and the regulations were not evenly enforced at the state level (USEPA, 2016; Brennan et al., 2021).

Though major industrial producers have voluntarily halted production of particularly health threatening PFAS types such as perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), these PFAS types have just been replaced with other types of
PFAS chemicals that have not yet been adequately studied but could have similar long term health impacts (CDC, 2017). Many studies have shown the dangers of PFAS to the environment and to humans, and other countries have more widely banned PFAS production and use, but the United States lags behind this progress leaving plenty of routes of exposure unregulated (Brennan et al, 2021).

3.2. Grouping and Naming of PFAS

PFAS is an umbrella term used for a variety of different PFAS classes that amount to thousands of different types of PFAS compounds (Guida et al., 2023; ATSDR, 2017). There are long-chain and short-chain varieties within the greater PFAS chemical class (Figure 1, Kwiatkowski et al., 2020). The distinction between long chain and short chain is the most important PFAS classification factor relevant to this study, since long chain PFAS such as PFOS and PFOA have been the center of existing regulations (Brennan et al., 2021). Recently, industry has attempted to replace these long chain varieties with short chain alternatives (Nascimento et al., 2018). Other relevant PFAS varieties are PFBS, a short-chain compound often used as an alternative for long-chain PFOS and PFOA in the face of regulations restricting long-chain PFAS use (Nascimento et al., 2018).
Figure 1: Breakdown of PFAS classes. Image Source: (Brennan et al, 2021).

3.3. Physical Characteristics of PFAS

PFAS compounds are made stronger by replacing the carbon hydrogen bonds (C-H bonds) with C-F bonds, one of the strongest types of bonds (NIEHS, 2023). These bonds take hundreds or thousands of years to break down in the environment, hence PFAS being called “forever chemicals” (NIEHS, 2023). The presence of fluorine (F) in the compound is what makes PFAS a “fluorinated substance”, defined as having at least one F atom (Buck et al., 2011; ATSDR, 2017). Since PFAS compounds have all of the C-H bonds in the tail replaced with C-F bonds (see Figure 2), this makes them per- or poly-fluorinated (Buck et al., 2011; Panieri et al., 2022). This change in bond structure makes the compounds much more resistant to heat, water, oil, and time, contributing to their persistence in the environment and the human body (Kwiatkowski et al, 2020). These traits are also what make PFAS so desirable in food packaging, clothing, etc. (USEPA, 2023b). The hydrophilic polar head of the PFAS molecule has variable composition, as indicated in Figure 2, but each PFAS molecule contains the hydrophobic fluorinated tail. The variation in the fluorinated tail between PFAS compounds is in the length of the tail (Buck et al., 2011). The longer the tail, the longer the PFAS compound takes to break down in the environment and human body, hence the added focus on these compounds in health studies and regulations (Kwiatkowski et al, 2020).
3.4. PFAS Uses and Sources of Release

A common use of PFAS since the 1970s has been aqueous film-forming foams (AFFFs), more commonly known as firefighting foams (USFA, 2023). PFAS has been valued by municipal fire and military departments because of its strong chemical bonds which work well to form films and cut off the oxygen supply to Class B fires (Johns Hopkins, 2023). Class B fires are defined as fires involving gasoline, alcohol, or oil-based paints (NFPA, 2006). Unlike other compounds, the bonds in PFAS are strong enough to resist breaking down in the presence of gasoline, alcohol, or oil-based paints effectively suppressing the fire (Johns Hopkins, 2023). Though research has begun to phase PFAS out of firefighting foams, a suitable alternative has not yet been found (USFA, 2023; Johns Hopkins, 2023). PFAS-containing firefighting foams remain in use at (USEPA, 2023b):

- Emergency response facilities
- Shipyards
- Military bases
- Firefighting training facilities
- Chemical plants
Refineries

These remaining sources release PFAS into the environment with each use, leaching into soil and water and causing risk of human exposure (USEPA, 2023a). Contamination of these environmental media with PFAS contributes to bioaccumulation of PFAS in fish tissue that could be consumed by humans and exposure to humans through recreational surface water contact or drinking water ingestion (Sunderland et al., 2019).

Another common use of PFAS is in household items such as (Kotthoff et al., 2016; USFDA, 2009; USEPA, 2023b):

- Non-stick cookware
- Certain foods
- Food wrappers
- Stain-resistant clothing and furniture
- Cleaning products
- Paints
- Personal care products etc.

Presence of PFAS in all of these items again is attributed to the bond structure in PFAS (USEPA, 2023a). PFAS makes materials containing the compound, such as food packaging, resistant to greases and heat, increasing the material’s longevity (USEPA, 2023a). Because of this characteristic, PFAS can be found in microwavable popcorn bags, pizza boxes, candy wrappers, etc., creating the potential for trace amounts of PFAS to be passed to the food and ultimately consumed (Seltenrich, 2020). Similar issues arise while cooking with PFAS-containing cookware or when using personal care items like dental floss and cosmetics that may end up in the mouth (Heather et al., 2021). PFAS can end up in dairy or other animal products if the livestock was exposed to PFAS, usually via contaminated drinking water, diet, or soil (USEPA, 2023b; Michigan PFAS Action Response Team, 2017).

PFAS have also been present in pesticides due to their manufacturing and packaging processes (USEPA, 2024a). Though currently there are no registered pesticide products that contain PFAS in the United States, there have been questions surrounding the production and storage of pesticides before being applied to crops (USEPA, 2024a). In 2022, USEPA released information from a study evaluating leaching potential of PFAS from fluorinated high-density polyethylene (HDPE) containers into the liquids they store (USEPA, 2024a).
Manufacturers ship and store pesticides in HDPE containers, causing concern about whether the containers could leach PFAS into the pesticide mixture that would then be applied to crops used for clothing and consumption (USEPA, 2024a). Manufacturers have voluntarily stopped shipment of any pesticide products stored in HDPE containers, hopefully closing this exposure route until investigation has concluded (USEPA, 2024a).

Internationally, most countries have ensured that certain PFAS compounds, like PFOS and PFOA, are not present in pesticides being applied to crops since the compounds were listed as a Persistent Organic Pollutant (POP) in 2009 under the Stockholm Convention (Guida et al., 2023). However, agriculturists have found loopholes to these restrictions. A study on Brazilian agricultural soils evaluated applications of sulfuramid (EtFOSA), an alternative to PFAS-containing pesticides (Guida et al., 2023). The study concluded that the EtFOSA would produce PFOS upon break down in the soil 15 days after application, demonstrating the dangers of this “safer alternative” (Guida et al., 2023). This brings into question whether other industries are also finding loopholes for existing PFAS restrictions and whether the alternatives being produced to replace PFAS are actually better for human health and the environment. The characteristics that make PFAS desirable in products such as AFFFs, household items, food packaging, HDPE containers, and pesticides are certainly valuable and hard to replicate. Similarly to plastics which were also developed for convenience and cheap production, society has developed a seemingly irreplaceable reliance on the convenient and durable nature of materials containing PFAS compounds.

3.5. **PFAS Life Cycle and Transport Through the Environment**

From the sources mentioned previously, PFAS enters and travels in the environment through a variety of pathways such as (Pennsylvania DEP, 2023):

- Wastewater discharge to stream from wastewater treatment plants (WWTPs)
- Wastewater discharge to stream from industrial production
- Air emissions from industrial production
- Firefighting foams
- Infiltration to soil and groundwater from agricultural sources

These pathways through the environment cause contamination of environmental media such as surface water, soil, groundwater, and air (Pennsylvania DEP, 2023). Because of these sources
and pathways, as visualized in Figure 3, it has been determined that PFAS has contaminated the global water supply (Domingo et al., 2019). A recent study found at least half of the United States tap water supply is exposed to PFAS compounds (Smalling et al., 2023). Additionally, PFAS is cycling through household supplies, seafoods, and biosolids in agriculture (Domingo et al., 2019).

Figure 3: Depiction of PFAS life cycle from source to environmental end point. Image Source: (PDEP, 2023).

Along these environmental transport pathways, other entities come into contact with PFAS resulting in additional exposure pathways to humans (Domingo et al., 2019). For instance, PFAS moving through soil can be uptaken by plants, contaminating the plant tissue and any fruit that comes from these plants (Sunderland et al., 2019). Additionally, PFAS traveling through surface water could contaminate fish within that water or livestock who drink the water.
A general flowchart of how chemical releases travel through the environment and result in human exposure and adverse health outcomes can be seen in Figure 4 (USEPA, 2023d). Consideration of the PFAS life cycle as a whole, as seen in Figure 3 above, can help to identify human exposure routes and shape policy decisions.

Figure 4: A flow chart of how contaminants, like PFAS, enter and travel through the environment, ultimately resulting in human exposure and potential for adverse health outcomes. Image Source: (USEPA, 2023d).

3.6. PFAS Uptake/Bioaccumulation

As PFAS has become more pervasive in the environment, observable concentrations in plant and animal tissues have also increased (Cheng et al., 2021; Haukas et al., 2007). PFAS can be uptaken by plants if the plant is growing in PFAS contaminated soils, being sprayed with PFAS-laden pesticides, or uptaking PFAS contaminated water from the soil solution (Nascimento et al, 2018; USEPA, 2024). Short chain PFAS varieties have a greater affinity for plant uptake versus long chain PFAS varieties because long chain PFAS are hydrophobic and will stay adhered to soil particles rather than being taken up by the plants in the soil solution (Wang et al, 2020). Though both chain length varieties of PFAS have similar toxicities, exposure to short-chain PFAS varieties are considered to be safer than long-chain because short chain-chain PFAS have a shorter half-life and can be filtered out of the body faster (Conder et al., 2008).
Additionally, PFAS has been shown to bioaccumulate in fish tissues for fish that live in PFAS contaminated water or consume smaller PFAS contaminated fish (Nascimento et al., 2018; Evich et al., 2022). A study done by the Centers for Disease Control (CDC) with data from the National Health and Nutrition Examination Survey (NHANES) in 2003 demonstrated that PFAS exposure has resulted in nearly the entire United States population having PFAS in their blood serum, specifically PFOS, PFOA, perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHS) (NIEHS, 2023) Live stock such as cattle can also accumulate PFAS in their tissues if they consume PFAS contaminated water (Sunderland et al., 2014). Bioaccumulation in fish and livestock can become another source of human exposure if people were to consume the contaminated fish, livestock meat, or any other livestock products such as milk, cheese, etc. (Ahrens et al., 2014).

4. Human Health Risk Associations

The following sections detail adverse human health outcomes associated with PFAS exposure, mostly focusing on PFOS and PFOA exposure associations.

4.1. Reproductive and Developmental Impacts

There have been several health studies produced since the 1990s that have demonstrated many long-term reproductive and developmental health impacts associated with PFOA and PFOS exposure (Song et al., 2023; Padula et al., 2023; USEPA, 2023b; Brown et al., 2020; Gao et al., 2021). In adults, chronic PFOA and PFOS exposure or acute elevated bloodstream levels can lead to infertility and increased odds of gestational hypertension (Darrow et al., 2013). This same study found a 27% increase in odds of gestational hypertension per log unit increase of PFOA and a 47% increase in odds of gestational hypertension per log unit increase of PFOS (Darrow et al., 2013). The study also revealed a statistically significant negative correlation between PFOS exposure and birth weight of full-term infants, suggesting higher exposures to PFOS resulted in lower birth weight of full-term infants (Darrow et al., 2013). Low birth weight in infants can have a series of negative health associations such as cognitive deficits, motor delays, cerebral palsy, and other behavior and psychological problems (K.C. et al., 2020). PFAS exposure in children can also lead to development of (Rappazzo et al., 2017):

- Attention Deficit Hyperactivity Disorder (ADHD)
● Dyslipidemia (imbalance of lipids with harmful cardiovascular implications)
● Impaired immune and vaccine responses
● Asthma
● Lower age of menarche (onset of first menstruation)

4.2. Organ Toxicity and Cancer Associations with PFAS

PFAS have also been linked to organ toxicity and other generally negative health effects (Brown et al., 2020; Borg et al., 2013; USEPA, 2023b). A study was produced in 2002 by the The United Nations Organization of Economic Cooperation and Development (OECD) analyzing PFAS and long-term effect on organ health. This study concluded that PFAS was bioaccumulative and toxic to humans (OECD, 2002). PFAS has been linked via multiple studies to (OECD, 2002; Steenland et al., 2013; Saikat et al., 2013; Lopez-Espinoza et al., 2013; Barry et al., 2013):

● Liver cancer
● Thyroid cancer
● Bladder cancer
● Kidney cancer
● Testicular cancer
● High cholesterol
● Impaired glucose metabolism
● Increased Body Mass Index (BMI)
● Impaired thyroid function
● Ulcerative colitis
● Decreased kidney function

Though long-term health studies on humans proving correlation between exposure and negative health outcomes are rare due to confounding variables, there have been a few strong long term health studies about PFAS exposure and cancer occurrences (OECD, 2002; Steenland et al., 2013; Saikat et al., 2013; Lopez-Espinoza et al., 2013; Barry et al., 2013). A study surveyed populations that lived in close proximity to a DuPont chemical plant that used PFOA in their manufacturing processes in 1951 (Barry et al. 2013). This survey took place over the course of 1 year approximately 4-50 years after exposure depending on how long the residents had lived
in the area (Barry et al., 2013). Participants were eligible if they lived, worked, or went to school within the contaminated water districts for at least 1 year (Barry et al., 2013). The DuPont chemical plant released PFOA into the Ohio River and air from the 1950s to 2001, also emitting into the groundwater which was used as the public drinking water source (Barry et al., 2013). A previous study had surveyed this population of residents living in close proximity to the chemical plant and relying on the drinking water, finding the average PFOA blood concentration to be 28 ng/mL, compared to the United States national average of 4 ng/mL (Barry et al., 2013). Table 1 depicts the types and number of cancer cases reported by residents in the area, revealing that 2,507 of the 32,254 participating residents reported various cancers after living in close proximity to a PFAS-using chemical plant and consuming PFOA contaminated groundwater (Barry et al., 2013).

<table>
<thead>
<tr>
<th>Cancer</th>
<th>No. reported</th>
<th>No. reported (had a medical record reviewed or a cancer registry entry)</th>
<th>No. validated [n (%)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladder</td>
<td>115</td>
<td>115</td>
<td>111 (96.5)</td>
</tr>
<tr>
<td>Brain</td>
<td>33</td>
<td>31</td>
<td>23 (69.7)</td>
</tr>
<tr>
<td>Breast</td>
<td>608</td>
<td>600</td>
<td>581 (96.6)</td>
</tr>
<tr>
<td>Cervical</td>
<td>383</td>
<td>245</td>
<td>22 (5.7)</td>
</tr>
<tr>
<td>Colorectal</td>
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<td>297</td>
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</tr>
<tr>
<td>Esophagus</td>
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<td>19</td>
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</tr>
<tr>
<td>Kidney</td>
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<td>117</td>
<td>113 (91.1)</td>
</tr>
<tr>
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<td>71</td>
<td>69 (87.3)</td>
</tr>
<tr>
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<td>15</td>
<td>10 (55.6)</td>
</tr>
<tr>
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<td>133</td>
<td>124</td>
<td>113 (85.0)</td>
</tr>
<tr>
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<tr>
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<td>19 (59.4)</td>
</tr>
<tr>
<td>Thyroid</td>
<td>98</td>
<td>97</td>
<td>87 (88.8)</td>
</tr>
<tr>
<td>Uterine</td>
<td>225</td>
<td>173</td>
<td>105 (46.7)</td>
</tr>
<tr>
<td>Total</td>
<td>3,589b</td>
<td>3,146</td>
<td>2,507c (69.9)</td>
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</table>

aValidated cases were limited to participants who reported the cancer and were subsequently confirmed either by Ohio/West Virginia cancer registry or medical record review; participants reported whether a doctor had ever told them they had a cancer or malignancy of any kind. bThese 3,589 cancers were self-reported by 3,292 participants; some participants reported more than one cancer type. cThese 2,507 cancers are among 2,361 participants.

Table 1: Number of reported and validated primary cancer cases among the cohort (n = 32,254) (Table Source: Barry et al., 2013).
4.3. At-Risk People Groups

Though PFAS exposure negatively impacts the health of all individuals, and all surveyed citizens of the United States have PFAS in their bloodstream, some people groups are more at risk than others (USEPA, 2023b). Children, pregnant and lactating women, industrial workers, and subsistence fishers have been identified as having increased risk for PFAS exposure, and therefore greater odds of suffering adverse health impacts (Darrow et al., 2013; CDC, 2022; Liu et al., 2022). Children and pregnant or lactating women are at higher risk or exposure because they breathe more air and drink more water per pound of body weight than the average adult, increasing their risk of exposure to PFAS through air and drinking water. Additionally, children can encounter a longer list of adverse health impacts with the risk of developmental deficits (Rappazzo et al., 2017). Industrial workers and subsistence fishers are at higher risk of exposure because their lifestyles increase PFAS exposure, subsistence fishers through increased fish intake and industrial workers through increased exposure to PFAS-laden air in their working environment (Liu et al., 2022; CDC, 2022). Policy should be protective of the most vulnerable people groups, and so these increased risk factors must be considered.

4.3.1. Children and Pregnant Women

Children have been found to be more at risk for PFAS exposure and adverse health impacts because of their habits which increase exposure and their early developmental stage which puts them at higher risk of developmental deficits compared to adults who are already fully developed (USEPA, 2023b). Developmental deficits and other health risks more prone to children were previously discussed in Section 4.1. Children tend to drink more water and eat more food per unit body mass than the average individual (USEPA, 2023b). Since drinking water and food consumption have been identified as frequent sources of PFAS exposure, this puts them at greater risk of the associated health risks (Berthold et al., 2023; Sunderland et al., 2019; Haukås et al., 2007; USEPA, 2023b). They also breathe more air per pound of body weight than an average adult, increasing their exposure from inhalation (USEPA, 2023b). Habits of young children such as crawling on floors and hand-to-mouth tendencies may increase their exposure to PFAS from (USEPA, 2023b):

- Carpet
- Household dust
4.3.2. Industrial Workers

Industrial workers are often exposed to PFAS if they are working in a facility that makes or processes PFAS or PFAS-containing materials (USEPA, 2023b). Specific industries at higher risk of increased exposure include chemical manufacturing, firefighting, and ski waxing (CDC, 2022). Types of exposure could be dermal from touching concentrated products or inhalation from breathing PFAS-contaminated air in the workplace (CDC, 2022). People living in close proximity to these facilities may also have increased exposure as detailed in previous sections (Barry et al., 2013).

4.3.3. Subsistence Fishers

Since PFAS bioaccumulation has been established in animal tissues like fish, people whose main diet consists of locally caught fish may be at greater risk for PFAS exposure and the subsequent adverse health outcomes (Liu et al., 2021). Certain immigrant or refugee communities might consume locally caught fish for economic or cultural reasons (Wattigney et al., 2021). A study evaluated the PFAS exposure of licensed anglers and Burmese refugees in New York State, fish was consumed more than three times per week, to examine how these people groups might be impacted (Liu et al. 2021). The study concluded that fish consumption from the Great Lakes Basin was associated with PFAS blood serum concentrations being elevated above the national average in the Burmese and licensed angler groups due to the increased exposure to PFAS through consumption of the contaminated fish tissue (Liu et al., 2021). This phenomenon of subsistence fishers having elevated PFAS exposure has been confirmed by multiple other studies of similar communities (Wattigney et al., 2021). In all
studies, PFOS was the most elevated (Liu et al., 2021; Wattigney et al., 2021; USEPA, 2023b). Many of these communities continue to eat the fish from PFAS-contaminated lakes such as the Great Lakes Basin because there is inadequate signage and public education warning the community about the dangers of PFAS exposure (Wattigney et al., 2021). In another example, New York State provides health fish consumption advice available in multiple languages, but the advice is not specific to PFAS contamination (Wattigney et al., 2021).

5. Regulatory Framework

Some of the main questions surrounding PFAS are the practicality of regulating. A main debate is whether PFAS should be regulated as an entire chemical class or regulated on an individual compound scale, such as PFOS and PFOA (Brendel et al., 2018; Brennan et al., 2021; Cordner et al., 2021; Dean et al., 2020). Effective regulation would consider a holistic view of the PFAS lifecycle, but certain aspects of the lifecycle or entire subclasses of PFAS are currently excluded from policy (Brennan et al., 2021). International PFAS policy began to form in the early 2000s, but PFAS policies in the United States did not begin until nearly 15 years later in 2016, suggesting a significant lag time for United States policy action compared to the rest of the world (Brennan et al., 2021).

5.1. PFAS Production Bans

Controlling PFAS pollution and exposure begins with regulation at the source, which is the production of PFAS. Other policies target control and treatment of PFAS once it has entered the environment, but PFAS production bans prevent PFAS from ever entering the environment to begin with. Whether the phase out of PFAS are voluntary or regulatory, PFAS production phase outs have been shown to decrease human exposure to PFAS (CDC, 2017; Brennan et al., 2021).

5.1.1. International PFAS Bans

PFAS policy at the source began in Europe in 2006 when the sale of PFOS, a long-chain PFAS type with negative health implications, was restricted to essential uses only (The European Parliament, 2006). The most recent progress towards a whole-class PFAS ban internationally is the proposal to ban PFAS published by the European Chemicals Agency (ECHA) in February 2023 (ECHA, 2023). This proposed ban would encompass more than 12,000 different types of
PFAS, whereas previous bans were only focusing on a few types of PFAS such as PFOA and PFOS (EPA, 2023b; The European Parliament, 2006). If approved, the ban could go into effect as early as 2026 (ECHA, 2023).

The proposal has yet to be approved, but it has created great controversy with claims that the ban is prioritizing policy over sound science (Spyrakis & Dragani, 2023). The overall sentiment is that the move away from PFAS could be a positive change, but it is a change that must be made on a class-by-class basis and gradually (Spyrakis & Dragani, 2023). Studies have demonstrated negative health associations with long-chain PFAS and some short-chain varieties, however other studies still argue that this does not mean every PFAS type is dangerous (Nascimento et al., 2018; Guida et al., 2023; Ameduri, 2023). Specifically, there is evidence that fluoropolymers do not have the negative health and environmental implications commonly associated with other types of PFAS (Ameduri, 2023). Industries and applications using fluoropolymers include (Wang et al., 2022):

- Automotive
- Aerospace
- Chemical
- Nuclear
- Electronics
- Medical devices
- Green-economy initiatives

Forcing industries to remove PFAS as a whole from their products could rush the process of finding a suitable alternative to PFAS, creating potential for replacement with subpar products (Spyrakis & Dragani, 2023).

Additionally, a rapid shift away from PFAS could rush research for an alternative and inhibit thorough health studies and toxicological characterization on the chosen alternative (Spyrakis & Dragani, 2023). The alternative compound could have its own suite of long-term human health impacts and pose more of a threat than the PFAS varieties that have not yet been proven harmful (Spyrakis & Dragani, 2023). Precautionary approaches should be taken for all PFAS varieties and any substitutes that might be used as alternatives.
5.1.2. United States PFAS Bans

In contrast to the European Parliament, the United States seems to place a federal emphasis on drinking water monitoring, reporting, and environmental cleanup rather than making progress towards any total PFAS bans. For instance, in February 2024, two federal regulations were proposed that would add nine PFAS to the list of Resource Conservation and Recovery Act (RCRA) hazardous constituents that would require cleanup (USEPA, 2024b). Also, in January 2024, seven PFAS were added to the Toxic Releases Inventory (TRI), requiring reporting in the 2024 reporting year. Further monitoring and reporting requirements will be discussed in Section 5.2. One of the only federal regulations that has resembled a PFAS ban was in January 2024 when USEPA finalized a rule that would prevent companies from starting or resuming the manufacture or processing of 329 PFAS types without complete USEPA review and risk determination (USEPA, 2024c). However, these compounds are ones that have not been made or used recently anyways, either because they were voluntarily phased out or are not as desirable in manufacturing (USEPA, 2024c).

Another federal regulation resembling a PFAS ban was the Department of Defense (DOD) issuing a new performance specification for firefighting foams used on military bases, stating that firefighting foams must be able to extinguish class B fires without the use of PFAS (USFA, 2023). This bans PFAS from continuing to be used in firefighting foams on military bases. In response, research has begun at Johns Hopkins to find an alternative to PFAS-containing firefighting foams, but a suitable additive that meets military specifications has yet to be found (USFA, 2023; Johns Hopkins, 2023). When a suitable additive alternative has been found, PFAS will be phased out of firefighting foams (USFA, 2023). This action resembles the European Chemical Agency ban in that it is forcing innovation by banning a compound that does not yet have a reasonable substitute.

Wider-reaching PFAS bans in the United States have largely been left to the states, with several states creating unique labeling requirements and banning the substance in products like food packaging, firefighting foam, and personal care products (USEPA, 2024b). Other states have taken little to no action (USEPA, 2024b). Overall, the United States seems to leave much regulation to the state and regulates on a chemical-class basis, not regulating PFAS as a whole. There are no proposed total federal bans on PFAS production.
5.1.3. Voluntary United States Phase Outs

There have been several industries, states, etc. in the United States that have voluntarily taken action to phase out PFAS production or find alternatives in the absence of regulatory restriction. Following emerging research and policy discussions, major producers utilizing PFAS in the United States, such as 3M and DuPont, voluntarily phased out PFAS production in the early 2000s (USEPA, 2004; USEPA, 2005). However, the voluntary phase out was only for specific subtypes of PFAS, like PFOS and PFOA, not for the PFAS chemical class as a whole. Most of these manufacturers simply replaced the PFOS and PFOA (long-chain varieties) with perfluorobutane sulfonic acid (PFBS) (short-chain variety) that had not yet become the center of PFAS regulations (Conder et al., 2008; Brennan et al., 2021). Because the short-chain varieties were not the focus of research and policy, they were believed to be safer alternatives (Conder et al., 2008). Recent studies from the USEPA have suggested that these “safe alternatives” may not actually be safer, citing that exposure to short-chain PFAS compounds still lead to negative health effects such as impaired kidney function, immune systems, liver function, reproductive system function, and organ development (USEPA, 2018a).

5.2. PFAS Levels, Monitoring, and Reporting in the United States

Several United States governmental agencies have public health goals and monitoring requirements for PFAS (USEPA 2016; USEPA 2018a; USEPA 2018b; USEPA 2023c; USEPA 2024a; USEPA 2024b; USEPA 2024c; USEPA 2024d). These health goals and monitoring requirements serve to inform public agencies and water systems on the difference between safe and dangerous PFAS exposure levels (USEPA 2016; USEPA 2018a; USEPA 2023a). These published levels are largely unenforceable in their present state and function more as suggested guidelines rather than enforceable regulations (NOAA, 2022; USEPA 2016; USEPA 2018a; USEPA 2023a). They also tend to follow industry action, rather than being proactively protective of human health (Brennan et al., 2021; USEPA 2024c).

5.2.1. Maximum Contaminant Levels

On March 14th 2023, USEPA announced proposed national drinking water Maximum Contaminant Levels (MCLs) for six PFAS types including PFOA, PFOS, perfluorononanoic acid (PFNA), hexafluoropropylene oxide dimer acid (HFPO-DA), perfluorohexane sulfonic acid
(PFHxS), and PFBS (California Water Boards, 2024; USEPA, 2024d). Under this National Primary Drinking Water Regulation (NPDWR), MCLs would establish legally enforceable levels, requiring public water systems to monitor for these PFAS compounds, notify the public of PFAS levels above MCLs, and reduce levels of PFAS in drinking water if levels exceed the MCLs (USEPA, 2024d). With a main source of PFAS exposure being from drinking water, enforceable monitoring and action levels could greatly reduce human exposures from drinking water (California Water Boards, 2024). USEPA is also pursuing acceptance of non-enforceable Maximum Contaminant Level Goals (MCLGs), which are more stringent (USEPA, 2024d). For example PFOA and PFOS MCLs are 4.0 parts per trillion (ppt) compared to 0.0 ppt MCLGs for both compounds (USEPA, 2024d). The 4.0 ppt MCL would be enforceable under the proposed NPDWR, but the 0.0 ppt MCLG would only be a suggested health-based goal.

5.2.2. Public Health Goals

To support the passing of these MCLs so that they can be enforceable, the Division of Drinking Water has requested that the Office of Environmental Health and Hazard Assessment (OEHHA) develop Public Health Goals (PHGs) for PFAS compounds under the proposed NPDWR (California Water Boards, 2024). PHGs are established by OEHHA as drinking water contaminant levels that pose no health risks, placing primary emphasis on public health protection (California Water Boards, 2024). PHGs inform MCLs, and MCLs for a contaminant are required to be as close to that contaminant’s PHG as technologically and economically possible (California Water Boards, 2024). Currently, there are no PHGs for PFAS, though that could change in the near future (California Water Boards, 2024).

5.2.3. Lifetime Health Advisories

In the interim between proposal and approval of the, USEPA has released lifetime health advisories (LHAs) for four PFAS compounds: PFOA, PFOS, PFBS, and HFPO-DA (California Water Boards, 2024). These LHAs established by USEPA do not inform MCLs, but they are otherwise similar to PHGs developed by OEHHA. They identify the concentration of a contaminant in drinking water that will not cause adverse health effects over a lifetime (California Water Boards, 2024). These levels advise agencies and public water systems in the absence of MCLs, but are not enforceable. They serve as guidelines.
5.2.4. Notification Levels and Response Levels

Similarly, notification levels (NLs) and response levels (RLs) are advisory action levels produced by the Division of Drinking Water based on recommendations made by OEHHA (California Water Boards, 2024). For contaminants that do not have established enforceable MCLs but pose enough risk to warrant advisories, NLs and RLs serve as precautionary measures in the interim until MCLs can be approved (California Water Boards, 2024). When drinking water levels for a contaminant, such as PFAS, exceed the NL, public water systems are advised to notify the community they serve about the potential risk (California Water Boards, 2024). Going beyond that, if drinking water contaminant levels, such as PFAS, exceed the RL, the water system is advised to take the water source out of service or provide water treatment if available (California Water Boards, 2024). In California, this advisory RL became an order for PFAS under Health and Safety Code as of 2020 (California Water Boards, 2024).

5.2.5. Threshold Limit Values

Threshold Limit Values (TLVs) are recommendations set by the American Conference of Governmental Industrial Hygienists (NOAA, 2022). TLVs are defined as the maximum average airborne concentration of hazardous material to which a healthy adult worker can be exposed to during an 8-hour workday and a 40-hour workweek over a working lifetime without experiencing significant adverse health effects (CDC, 2022). This means they only apply to air inhalation for adult workers in industrial work settings. They are composed of time-weighted average (TWA) concentration, ceiling value, and short-term exposure limit (STEL) value of the contaminant, in this case PFAS (NOAA, 2022).

The TWA is defined as the concentration of a contaminant averaged over a workday, assumed to be 8 hours long (NOAA, 2022). Ceiling value is considered to be the concentration of a toxic substance in air that should not be exceeded at any given time during the workday, even for a short time period (NOAA, 2022). STEL is the TWA concentration of a contaminant over a 15 minute period that ACGIH recommends not to exceed. All of these values are obtained by sampling the worker’s breathing zone (NOAA, 2022). An example of how these components interact with each other can be seen in Figure 5. These components all contribute to the advisory health guidelines that are TLVs.
Figure 5: An example of how a contaminant concentration can fluctuate in an industrial worker’s breathing zone throughout the day. The concentration may be above or below the TWA, but it never exceeds the ceiling value. Image Source: (NOAA, 2022).

ACGIH has released TLVs for PFAS, but only for 3 types of PFAS compounds: perfluoroisobutylene (PFIB), perfluorobutyl ethylene (PFBE), and ammonium perfluorooctanoate (APFO) (CDC, 2022). APFO is a salt of PFOA (CDC, 2022). Though ACGIH TLVs are acknowledged by National Institute for Occupational Safety and Health (NIOSH) and inform what is considered to be a safe working environment, they are health based guidelines not regulatory standards.

6. Methods

To address the research questions established earlier on, I performed a literary synthesis, produced tables and charts of the literary synthesis results, conducted an interview with a PFAS consultant, and analyzed the strengths and weaknesses of current and proposed PFAS policy strategies.
6.1. Literature Synthesis, Tables, and Graphs

I sourced literature from Scopus, an Elsevier database, using the search phrase “{PFAS sources} AND exposure” within an article’s title, abstract, or keywords. I considered literature from scientific peer-reviewed journals and policy review articles written in the English language and published 2014-2024. I conducted the literature synthesis on April 6th, 2024. The search phrase and restrictions returned 14 documents, 13 of which I deemed relevant to the scope of this research. Other similar search terms I tested in Scopus yielded larger result pools, however I deemed the majority of the results irrelevant to the human health scope of this study. From literary synthesis of PFAS sources and pathways in the environment, I produced a table, chart, and conceptual site model to visualize how humans are exposed to PFAS from its many sources and life cycle stages. I found incidental sources via Google and Scopus searches for more specific topics pertaining to individual agencies and PFAS policies for consideration in the strengths, weaknesses, opportunities, and threats (SWOT) analysis. I deemed the incidental sources relevant and credible if they were peer-reviewed or published by a government agency relevant to the specific policy. I did not use any incidental sources in the formal literature synthesis conducted April 6th, 2024 to establish primary PFAS sources.

6.2. PFAS Consultant Interview and SWOT Analysis

To gain perspective on current limitations to PFAS policies that are adequately protective of human health, an interview was held with a PFAS consultant from Environmental Resources Management, Inc. (ERM). This interview informed recent progress in United States PFAS regulation and existing gaps and helped shape this study’s perspective on management recommendations. A SWOT analysis was conducted for existing and proposed PFAS production bans and screening levels in the United States and Europe to analyze strengths and weaknesses of these approaches.

7. Results

7.1. PFAS Sources and Exposure Routes

To highlight the largest PFAS sources that might contribute most to human exposure, a scoping review of literature linking PFAS sources and exposure was completed through Scopus,
an Elsevier database. 14 journals and reviews were returned in the search, 13 of which were deemed relevant to this research. Each journal and review was read to identify cited PFAS sources and which exposure route these sources were found to be associated with. A full list of literature reviewed is synthesized in Table 2 below, along with the identified PFAS sources and associated exposure routes.

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Table 2: Literature synthesis of Scopus journals and reviews mentioning PFAS sources and exposure in their titles, abstracts, or key words. Identification of which sources and exposure routes mentioned in each source.
There were approximately 10 identified PFAS sources repeated across multiple literature sources. These repeated PFAS sources included:

- AFFFs
- WWTPs
- Cleaning products
- Industrial manufacturing
- Textiles
- Airports
- Landfills
- Personal care products
- Agriculture
- Food packaging

The number of articles each PFAS source was cited in as an exposure risk to humans can be seen in Figure 6. Other miscellaneous PFAS sources were mentioned in the reviewed articles, but not repeated. These sources are accounted for in the “other” column in Figure 6. The most commonly referenced source of PFAS release into the environment resulting in human exposure was AFFFs, followed by industrial manufacturing. In articles that discussed AFFFs and industrial manufacturing, main associated human exposure pathways were through:

- Air
- Drinking water
- Surface water dermal contact
- Fish consumption
I built a conceptual site model to better visualize how PFAS release into the environment leads to various human exposures. This model was built from sources, environmental transport pathways, and exposure endpoints that I identified in the literature review (Figure 7). Primary sources, or sources identified at the very beginning of the PFAS life cycle, were largely identified to be industrial production, AFFFs, and agriculture. From the primary source of industrial production, PFAS travels into household products, air, and water.

From the PFAS sources identified in the literature synthesis, exposure routes were also identified in the literature synthesis studies and other incidental studies. From household products, humans can be exposed via accidental ingestion or ingestion of food contaminated from nonstick cookware or packaging. Ingestion of household products could also include oral
exposure from personal care products like dental floss or lipstick. Dermal contact from household products could include exposure from personal care products like makeup products, contact with PFAS-containing upholstery or furniture, and contact with PFAS-containing textiles or clothing. PFAS exposure from air can occur indoors or outdoors. PFAS indoor air inhalation exposures happen most commonly for individuals in residential or industrial settings. Air exposures can also come from agricultural sources if PFAS-laden pesticides are aerosolized upon application. Soil is another exposure media contaminated by agriculture. The human exposure route is through dermal contact with the soil, though this is considered to be a minor exposure risk unless an individual is living and working in the contaminated soil. AFFFs can also leach into soils, making this exposure route applicable to soils as well. AFFFs and agriculture both contaminate water, including surface water, groundwater, and water treated in WWTPs. Water contamination can result in direct PFAS exposure through ingestion of drinking water or dermal contact for recreational or hygiene purposes. PFAS contamination of water can also lead to indirect exposures through plants and animals that uptake the PFAS-contaminated water. Plants that uptake PFAS in water from the soil solution can produce PFAS-contaminated fruits. Consumption of these contaminated fruits would create a PFAS exposure route to humans. Similarly, if livestock drink PFAS-contaminated waters, their tissues and other animal products like milks and cheeses would be contaminated, creating an exposure route to humans if consumed.
Figure 7: Conceptual site model of human exposure routes composed from literature synthesis of PFAS sources.

7.2. SWOT Analysis and Discussion of Policy Approaches

There are several policy approaches that have been implemented or proposed, as discussed in my interview with a PFAS consultant at ERM, yet PFAS remains a health threat for much of the human population (J. McDonough, pers. comm., March 12, 2024; NIEHS, 2023; CDC, 2017). The regulatory approach for PFAS source control is divided into three categories for this SWOT analysis: banning PFAS as a whole chemical class, banning PFAS on an individual compound basis, and imposing more conservative health-based screening levels. Each of these regulatory approaches have their own strengths and weaknesses, identified from incidental searches and analyzed in subsequent sections.

7.2.1. Whole Class PFAS Bans

Description: Whole class PFAS bans aim to ban all types of PFAS compounds, restricting use on every single one of the thousands of PFAS variations (ECHA, 2023). Progress
towards this type of ban has mostly been observed in Europe, with the European Union now proposing to ban PFAS as a class entirely (ECHA, 2023). This is the first whole-class PFAS ban to be proposed, with implementation starting as early as 2026 if approved (ECHA, 2023). Regulations preceding this ban have focused on specific long-chain PFAS compounds, such as PFOA and PFOS only (European Parliament, 2006). The proposal will put pressure on industry to permanently phase out all PFAS from their products in the next few years, forcing progress on finding a suitable alternative to PFAS in their products. Previously, regulatory action has seemed to follow industry’s lead. For instance, putting restrictions on PFOA and PFOS after industry had already voluntarily phased them out of their manufacturing (USEPA, 2004; USEPA, 2005).

**Strengths:** Whole class PFAS bans are an ambitious ideal, but this pressure to innovate and find a suitable alternative might be the only way PFAS can be effectively eliminated from production cycles (J. McDonough, pers. comm., March 12, 2024). Industry claims whole-class PFAS bans are not feasible because they have not been able to find a safer alternative to PFAS for their products (Spyrakis & Dragani, 2023). However, whole-class PFAS bans would essentially force innovation to solve this problem (J. McDonough, pers. comm., March 12, 2024). Discovery of a suitable alternative to PFAS could be found much faster through regulatory pressure rather than industry being left to voluntarily phase out all PFAS compounds on their own. Presently, when an industry phases a long-chain PFAS like PFOS or PFOA out of their manufacturing process, the given PFAS compound is just replaced with another PFAS compound that has either been deemed “safer” or is just unstudied, like many short-chain PFAS compounds (Brennan et al., 2021). Stopping this input of PFAS into production and the environment paired with improvement of remediation technologies could greatly reduce human exposure risk and any subsequent adverse health outcomes (CDC, 2017; NIEHS, 2023). The ban would also be final. It would eliminate any guess-work and testing required around new PFAS compounds being invented because there would be no new PFAS compounds being invented or presently used. The focus could then shift from production regulation to removing existing PFAS from the environment via remediation or removal, further reducing human exposure risk. As long as certain PFAS varieties remain in circulation, uncertainty about exposure and long term adverse health outcomes remains (Conder et al., 2008; Brennan et al, 2021; USEPA, 2018a).

**Weaknesses:** Whole-class PFAS bans may not have enough data behind them to be widely adopted (Spyrakis & Dragani, 2023). There are thousands of different PFAS compounds,
and not all have been studied to account for long term human health implications before being allowed to go to market (Rayasam et al., 2022). There are many perspectives on this, but those with the perspective of “innocent until proven guilty” when it comes to chemical compounds claim that not all PFAS compounds have been proven dangerous, so not all PFAS compounds should be banned (Spyrakis & Dragani, 2023). This perspective is contrary to Europe’s cautionary approach, so the weight of this argument in Europe with their current proposed PFAS ban is not certain. The United States would be unlikely to pass any whole-class regulation like this though because of the lack of health data on each and every PFAS compound (J. McDonough, pers. comm., March 12, 2024). It is still believed that short-chain PFAS are a safer alternative to long-chain PFAS compounds, though recent research is beginning to say otherwise (Spyrakis & Dragani, 2023; Conder et al., 2008; Brennan et al, 2021; USEPA, 2018a). There are also claims that whole-class PFAS bans are too controlling of markets and industry, that progress should be more market-driven instead of governmentally enforced (Spyrakis & Dragani, 2023). This argument assumes that consumers can make their own choices about the products they use, and that if consumers choose to move away from products containing PFAS, the market will naturally shift to accommodate the consumer’s demands. Whole-class PFAS bans also do not address PFAS that have already entered the environment or products being sold in stores (ECHA, 2023). These bans would need to be coupled with improved remediation technology and sale restrictions to effectively prevent human exposure. Regulators would also want to ensure adequate health studies were conducted on any alternatives being produced to comply with a whole-class PFAS bans. There is concern that bans imposed too quickly would not leave enough time for long term health studies, creating the potential for long term health impacts of exposure to these PFAS alternatives to be overlooked, similarly to how long term health impacts were overlooked when PFAS was introduced (Spyrakis & Dragani, 2023).

7.2.2. Restricting PFAS Compound by Compound

**Description:** Regulations on PFAS compound by compound restrict PFAS compounds based on their use and relative health risks as research and data emerges, as seen with PFOS and PFOA. A specific example of this would be the European Union restricting PFOS to essential uses only (European Parliament, 2006). This restriction only applied to PFOS, not any other PFAS class or compound. Another example would be the USEPA banning use of 329 PFAS
compounds without complete USEPA review and risk determination (USEPA, 2024c). This regulation was wider reaching, but still did not apply to PFAS as whole class and focused on PFAS compounds that had already been phased out of production voluntarily by industry (USEPA, 2024c). This type of regulation is more commonly seen in the United States and other countries and is usually backed by data and health studies to inform which compounds are regulated (Brennan et al., 2021).

**Strengths:** The data backing these compound-by-compound regulations typically make them hard to dispute. Additionally, as the health data comes out, industry tends to voluntarily shift away from these compounds to appease consumers and avoid negative public perception before the government passes any kind of regulation (USEPA, 2004; USEPA, 2005). This means that when these types of restrictions are passed, they are not usually met with much resistance. These compound-by-compound regulations are able to achieve reduced human exposure to dangerous PFAS chemicals without producing heavy controversy (CDC, 2017; Brennan et al., 2021). They achieve reduction of human exposure and adverse health impacts by targeting PFAS compounds that have been proven to be harmful (CDC, 2017). They also do not over control industry and the market since they allow other PFAS compounds to be substituted for the harmful PFAS compounds (Spyrakis & Dragani, 2023).

**Weaknesses:** Compound-by-compound regulations tend to lag far behind the introduction of novel PFAS compounds and emergence of data suggesting adverse human health impacts (Rayasam et al., 2022). These regulations rely heavily on an overwhelming burden of proof in terms of adverse health impacts, but these health studies take time to produce and negative health implications may not be observed for decades after exposure (Rayasam et al., 2022). An argument can also be made that they cater too heavily to industry and lobbyists who pressure agencies to delay PFAS restrictions as long as possible (J. McDonough, pers. comm., March 12, 2024). If there is a non-standardized burden of proof required for these regulations to be passed, it becomes easy to poke holes in studies and argue that the data is not there, delaying regulation (Rayasam et al., 2022). Additionally, compound-by-compound regulations seem to only temporarily solve the issue of human exposure and subsequent health impacts (Conder et al., 2008; Brennan et al, 2021; USEPA, 2018a). When compound-by-compound regulations are imposed, industry will simply shift to a different kind of PFAS compound that has not been studied heavily enough to be regulated yet (Conder et al., 2008; Brennan et al, 2021; USEPA,
2018a). This does not solve PFAS human exposures in the long term or ensure that substitutes are actually safer than the compound that is being substituted (Brennan et al., 2021). Compound-by-compound regulations may be too slow to keep up with widespread PFAS uses and novel PFAS compounds being introduced.

7.2.3. Improving Health-based Screening Levels

*Description:* Health-based screening levels are risk-based concentrations determined by the USEPA that combine exposure information assumptions with USEPA toxicity data (USEPA, 2024e). These screening levels can be used to inform the magnitude of environmental and human health concerns associated with each compound (USEPA, 2024e). Levels of contamination above the USEPA screening level suggests that further evaluation of potential risks by site contaminants may be necessary (USEPA, 2024e). Contaminant values below the screening level indicates the daily human exposure is likely to be without adverse health risks (USEPA, 2024e). Screening levels can serve as initial cleanup goals, but are not cleanup standards (USEPA, 2024e).

*Strengths:* Imposing conservative health-based screening levels protects individuals from any notably dangerous exposures to PFAS. They provide guidance for cleanup and keep industries in check in terms of human health risk due to contaminant exposure (USEPA, 2024e). Screening levels address risk from a variety of pathways including soil, air, and drinking water for multiple people groups including residential and commercial/industrial exposures (USEPA, 2024e). They provide a threshold for how much exposure is too much exposure, guiding cleanup efforts and regulatory guidelines (USEPA, 2024e). Without these screening levels, an agreeable reference point for what constitutes a present danger with PFAS might be difficult to achieve.

*Weaknesses:* Screening levels serve as a reference point for some people groups and scenarios, but not all people groups or scenarios, leaving multiple exposure routes unchecked. With values only addressing exposures from drinking water, air, and soil, other exposure routes such as exposure from cookware or ingestion of contaminated fish are not addressed (USEPA, 2024e). Therefore, screening levels alone should not inform what poses a danger in terms of PFAS exposure and should only serve to aid regulatory decisions. They should not be the sole basis for decisions. A summary of this analysis can be seen in Table 3 below.
<table>
<thead>
<tr>
<th>Strategy</th>
<th>Strengths</th>
<th>Weaknesses</th>
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| PFAS Whole Class Bans | · Forces innovation  
· Eliminates production  
· Reduces human exposure  
· Eliminates guesswork  
· Eliminates testing worries  
· Precautionary approach  
· Most protective of public health | · Lacking data  
· Lacking evidence  
· Difficult to pass  
· Costly to implement  
· Interference with markets  
· Does not address environmental contamination  
· Preventative not curative  
· Rushed approval of alternatives |
| PFAS Case-by-case Bans | · Backed by data  
· Tends to follow voluntary action  
· Least resistance  
· Reduces human exposure  
· Not overly controlling of markets | · Lag behind introduction of novel compounds  
· Burden of proof  
· Limited authority for necessary information  
· Political interference  
· Cater too heavily to industry  
· Delays in regulation  
· Alternatives are other PFAS compounds  
· Temporary solution until new data emerges |
| Screening Levels & Monitoring | · Provide basis for risk evaluation  
· Monitors concentrations  
· Indicator of public health risk  
· Monitors public health risks  
· Data driven  
· Can be enforceable  
· Drives public perception | · Does not consider all scenarios or peoples  
· Multiple exposure routes not considered  
· Underestimates public health risks  
· Not always enforceable  
· Gaps in processes lead to weak regulation |

**Table 3:** Summary of SWOT analysis.

### 8. Discussion and Management Recommendations

Though there are several existing and proposed PFAS policies, many of the sources and exposure routes, as identified in Section 7.1, are left unregulated. Sources and exposure routes that are regulated may still have gaps or limitations that prevent effective protection of public health. There are strategies that can be implemented to address these limitations, but there is debate on the best path forward. In addition to policy issues, public education on PFAS is also
lacking. This lack of adequate knowledge sharing on the risks of PFAS results in already vulnerable communities being most heavily impacted. Given the known human health risks associated with PFAS exposure and demonstrated instances of PFAS production still resulting in exposure through unregulated pathways, improvements to current strategies are necessary. Changing the way PFAS is addressed at the source, passing enforceable screening levels, and improving public awareness of PFAS exposure and health risks are ways to better protect public health.

8.1. PFAS Source Control

There needs to be some level of control over PFAS sources through production and use regulations, though there is debate on the best way to go about this. A whole-class PFAS ban might seem like the simpler approach because it is most protective of public health and is a single regulation over all PFAS types, uses, and production (ECHA, 2023). It is regulating the few primary sources of PFAS rather than regulating each secondary source and exposure route individually or focusing on monitoring requirements (ECHA, 2023). However, as established in the SWOT analysis, this type of whole-class regulation would be unlikely to pass in the United States because of the political and industry pushback it would face. Opponents to these whole-class bans cite lack of data proving danger for each individual PFAS compound and therefore say whole-class PFAS are a governmental overstep, allowing the government to interfere too heavily with the market (Spyrakis & Dragani, 2023). There are also concerns about rushed approvals of alternatives to PFAS to meet regulatory deadlines (Spyrakis & Dragani, 2023).

There is validity in these concerns about whole-class PFAS bans, especially when it comes to concerns about rushed approvals of PFAS alternatives, causing potential for new compounds with their own suites of long-term health impacts to be introduced. Driving innovation to find suitable alternatives to PFAS is a good thing, but the process cannot be rushed (J. McDonough, pers. comm., March 12, 2024). However, this does not mean that the business can continue as normal. If industry wants to continue to use PFAS in their manufacturing or products, no matter the compound, they need to prove the compound is not a threat to human health before it is mass marketed. Evaluation of public health prior to marketing of new synthetic compounds is currently required under the TSCA, as discussed in Section 1, though to varying degrees of effectiveness (Rayasam et al., 2022). This act is enforced by the USEPA. However,
the burden of proof lies with the USEPA to prove the compound poses “unreasonable risk” in order to have authority to regulate it, rather than the manufacturer having to prove the compound is safe in order to market it. In their evaluations, the USEPA also often underestimates risks associated with the given compound (Rayasam et al., 2022). They have a history of not considering all exposure routes associated with use of that compound (Rayasam et al., 2022).

Further amendments to the TSCA are needed to redistribute the burden of proof from the USEPA onto the manufacturer instead. This would also shift the general perspective of chemical approval from needing approval to regulate compounds to instead needing approval to use compounds to begin with. The United States has been far too cavalier in approving chemicals for mass market without accurately evaluating the long-term human health impacts of use. For example, only 10 of 86,000 new chemicals introduced since the implementation of the TSCA have been regulated, with chemicals like asbestos being approved for market despite known health risks (U.S. Government Accountability Office, 2013; Rayasam et al., 2022). That perspective needs to shift to a more precautionary approach with how new synthetic compounds are being approved. Europe’s approach to new chemicals is much more precautionary and protective of human health. For example, they have been restricting PFAS use as a whole class since 2009 and are now moving towards a whole-class PFAS ban (The European Parliament, 2006; ECHA, 2023). While a whole-class PFAS ban may not be the most feasible approach, the United States may benefit from following Europe’s precautionary approach lead.

8.2. Enforceable Screening Levels and Monitoring

A change in how new chemicals are being evaluated could be supplemented with improving screening levels and monitoring requirements for existing PFAS compounds already in circulation. With the exception of PFAS MCLs that apply to drinking water concentrations under the Safe Drinking Water Act (SDWA), there are not any enforceable screening levels for PFAS (USEPA, 2024b). All other health-based concentrations or risk factors are released as regulatory guidelines or public health goals, but they have no regulatory teeth. As they are, they are too weak to effectively protect human health. There are multiple exposure pathways left unregulated including soil, air, and household products. Even for exposure pathways that do have enforceable screening levels, like MCLs for PFAS, the regulatory process takes too long to be considered preventative in any way. for drinking water which will now be regulated with the
MCLs, the MCLs are only for six PFAS types and the regulatory process was slow moving. It took until 2023 for the USEPA to propose the MCLs for these six PFAS types, another year to get them passed, and the regulatory requirements of them will not be implemented until 2027. From proposal to implementation, it will have taken 4 years for a policy to take action in protecting public health. On its own, the strategy of producing screening levels and monitoring results for PFAS compounds in circulation is not a sustainable way of protecting human health. Improvements to these processes can be a temporary solution until better source control is attained through improved novel chemical evaluation as discussed in the previous section.

8.3. Public Awareness

There is also the issue of public awareness. In the studies done on subsistence fishing communities in the United States, there were significant PFAS knowledge gaps in the communities (Liu et al., 2021; Wattigney et al., 2021). In the example of fishing communities near The Great Lakes, people may have known the lakes were contaminated, but they did not know the full extent of the contamination or the health risks associated with exposure. In some cases, there were no accessible fish advisories. If there were fish advisories, they were not always in the right language. Additionally, the fish advisories did not contain any information about PFAS exposure and health risks. PFAS need to be evaluated in surface waters like rivers and lakes so that fishing advisories can be posted for PFAS when concentrations exceed levels of concern. When fishing advisories are released, they need to be published in all relevant languages.

Additionally, many stores still carry household products like cookware that contains PFAS. These products may be marketed with labels that say “PFOA free”, but these items may still contain other PFAS compounds like PFOS. In a 2023 study, it was found that roughly 45% of respondents had never heard of PFAS and did not know what it was (Berthold et al., 2023). In this same study, only 11.5% responded that they knew their community had been exposed to PFAS (Berthold et al., 2023). In reality, every individual in the United States has PFAS in their blood serum (NIEHS, 2023). Most people do not know about PFAS, and if they do, they do not have enough technical knowledge to know the difference between the different PFAS acronyms and what the acronyms imply. The distinction between these acronyms is important since they are indicative of different PFAS compounds, all with varying health risks depending on the
length of the fluorinated tail in the molecule. Ultimately, people may not know what they are exposing themselves to. There should be more transparency in labeling so people can be better informed and improvements to public awareness of PFAS so people can better understand the information being presented to them.

In California, Proposition 65 (enforced by OEHHA, a branch of the California Environmental Protection Agency) requires businesses to provide warnings to consumers about significant exposures to chemicals that are known to cause cancer, birth defects, or other reproductive harm (OEHHA, 2024). There are approximately 900 chemicals on this list, including two types of PFAS (PFOA and PFOS) (OEHHA, 2024). This means for products containing PFOA or PFOS, warning labels must be placed on the packaging stating that the product contains chemicals that are known to cause cancer, birth defects, or other reproductive harm (OEHHA, 2024). These labeling requirements should be extended to other types of PFAS by OEHHA in California and required at the federal level by the USEPA as long as PFAS remains in household products.

With the improvement in product labels and warnings, there also needs to be increased public awareness campaigns so people can better understand the information being presented to them. PFAS labels are not helpful if 45% of consumers do not know what PFAS is and 88.5% of people think they have not been exposed to it (Berthold et al., 2023). There have been successful public outreach and education campaigns for other endocrine disruptors like Bisphenol A (BPA) and certain pesticides like dioxins. Familiarity and perception of risk was improved for these compounds through media campaigns, distribution of information by health professionals, and educational resources in schools. Similar strategies could be applied to increasing public familiarity with various PFAS compounds.

8.4. Summary of Management Recommendations

A summary of my management recommendations from the previous sections is as follows:

1) Based on the number of unregulated PFAS compounds and sources identified in background research and literature synthesis, the USEPA should amend the TSCA to place the burden of proof on the manufacturer to prove safety of their novel compounds before marketing, rather than the USEPA having to prove danger before regulating. The
manufacturer’s novel compound assessments should be subject to USEPA review and final approval.

2) Based on the number of unregulated PFAS exposure routes identified in my conceptual site model, the USEPA should move to implement enforceable screening levels and monitoring requirements for all environmental media, including air, water, and soil, to ensure PFAS concentrations are not exceeding levels deemed to be a threat to human health.

3) Based on the health threat of PFAS exposure from consumption from contaminated fish (identified in literature synthesis) largely being attributed to lack of awareness, individual state and county agencies need to issue fish advisories clearly stating information on the presence and health risks of PFAS exposure, ensuring these advisories are language-accessible to their communities.

4) Based on the threat of PFAS exposure from household items identified in literature synthesis, USEPA should adopt a federal regulation similar to California Proposition 65, requiring businesses to provide warnings to consumers about significant exposures to chemicals, such as PFAS, that are known to cause cancer, birth defects, or other reproductive harm.

5) To ensure the prior labeling recommendation is effective, product labeling needs to be coupled with increased public awareness so that consumers can make informed decisions. State and local agencies should implement PFAS educational resources via schools, media campaigns, and health centers, including information on common PFAS exposure routes and the health risks associated with PFAS exposure.
9. Conclusion

Ultimately, PFAS policy implementation is on a positive trajectory. The PFAS issue has been gaining heavy media attention which has been driving public perception, voluntary industry shifts, and regulatory action. PFAS monitoring and regulatory issues are also getting the funding they need for improvement which is encouraging. There is starting to be more effluent characterization of PFAS concentrations for landfills, industrial sites, and wastewater treatment sites. Though progress may be slow, progress is being made and solutions are being worked towards. However, effort still needs to be made to ensure the strengths of the policies being implemented. Currently, there are still gaps in regulatory processes that allow PFAS to continue being produced and circulated in our economy, causing a threat to public health. Overall, public awareness of PFAS exposure and the associated health risks needs to increase and the United States needs to shift to a more precautionary approach with PFAS and chemicals in general.
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