Review

Forever Chemicals PFAS Global Impact and Activities, Cascading Consequences of Colossal Systems Failure: Long-Term Health Effects, Food-Systems, Eco-Systems

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Review

Forever Chemicals PFAS Global Impact and Activities, Cascading Consequences of Colossal Systems Failure: Long-Term Health Effects, Food-Systems, and Eco-Systems

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Abstract: Per- and polyfluoroalkyl substances (PFAS) are found everywhere including food, cosmetics, and pharmaceuticals. This review introduces PFAS comprehensively, discussing their nature, identifying the interconnection with microplastics, and their impacts on public health and the environment. The Human cost of decades of delay, cover-ups, and mismanagement of PFAS and plastic waste has been out-lined and briefly explained. Following that PFAS and long-term health effects have been critically assessed. Risk assessment has then been critically reviewed mentioning different tools and models. Scientific Research and Health Impacts in the United States of America have been critically analyzed taking into consideration the Center for Disease Control (CDC) PFAS Medical Studies and Guidelines. PFAS impact, activities, and studies around the world have focused on PFAS Levels in Food Products and Dietary Intake in Different Countries such as China, European countries, USA and Australia. Moreover, PFAS in Drinking Water and Food have been outlined with regard to risks, mitigation, and regulatory needs taking into account chemical contaminants in food and their Impact on health and safety. Finally, PFAS impact and activities briefings specific to regions around the world refer to Australia, Vietnam, Canada, Europe, and the United States of America. Crisis Multi-Faceted Issue, exacerbated by mismanagement has been discussed in the context of applying problem-solving analytical tools: the Domino Effect Model of accident causation, the Swiss Cheese Theory Model, and the Ishikawa Fish Bone Root Cause Analyses. Last but not least, the PFAS impact on the Sustainable Development Goals (SDGs) of 2030 has been rigorously discussed.

Keywords: forever chemicals; PFAS; PFOS; health effects; health risks; toxicity; soil health; water quality; air quality; food safety; waste mismanagement; food security; SDG; sustainability; systems failure

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1. Introduction

1.1. PFAS Origins and Complacency

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic chemicals that have been used since the 1940s. Due to their unique ability to repel oil and water, PFAS have been extensively utilized in a wide range of consumer products, including non-stick cookware, water-repellent clothing, stain-resistant fabrics, fire-fighting foams, grease-resistant food packaging, cosmetics, pharmaceutical containers, pesticides, and more [1] (ITRC, 2020).

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Initially developed by chemical manufacturers like 3M and DuPont in the mid-20th century, PFAS became widely adopted in industrial and consumer products for their durability and resistance to chemical breakdown. Unfortunately, these same attributes have led to their persistence in the environment and human body, where they accumulate over time [1].

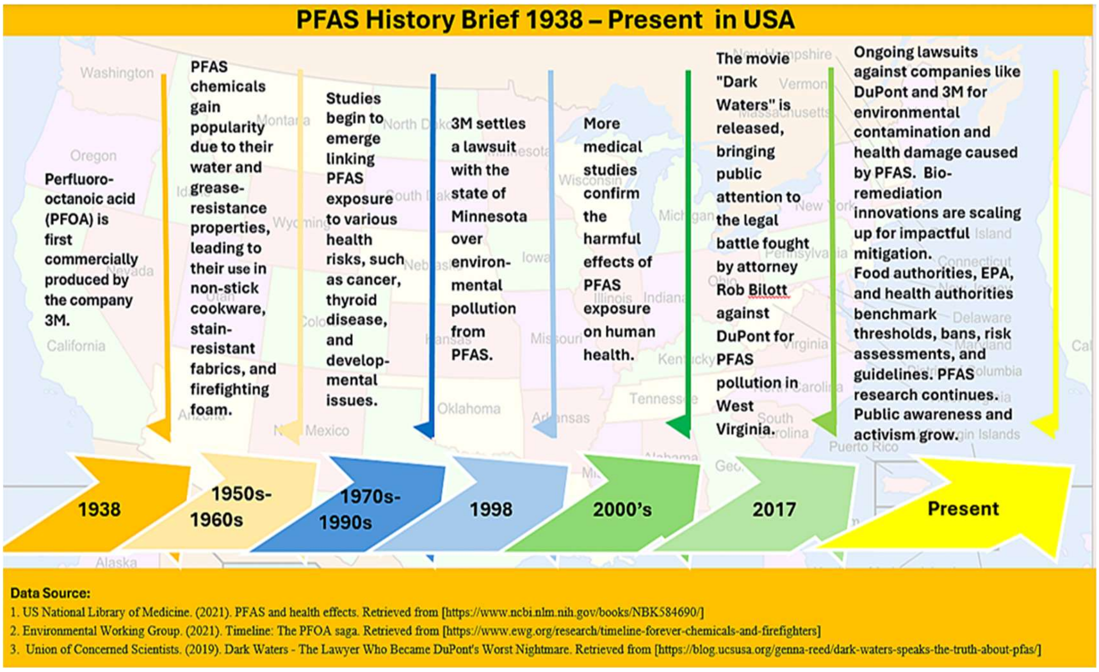

Figure 1. Timeline of PFAS Development and Impact (1938-Present) History Brief 1938 to Present in the USA, [2–4]] (EWG, 2021; UCUSA, 2019; NIH, 2021).

•**The PFAS Crisis: In Plain Sight:** The self-inflicted insidious invasive ubiquity of the PFAS Crisis (1940s to Present): Per- and polyfluoroalkyl substances (PFAS) were first developed in the late 1930s and became widely used in the 1940s for their unique properties, such as resistance to heat, water, and oil. These "forever chemicals" have since infiltrated various industries, including textiles, food packaging, and firefighting foams. Their persistence in the environment and the human body has led to widespread contamination, making them nearly ubiquitous in modern life [1] (ITRC, 2020).

•**The Power of Chemical Companies:** Chemical giants like 3M, DuPont, and Chemours have played significant roles in the proliferation of PFAS. These companies have leveraged their economic power and political influence to shape regulations and public perception, often downplaying the risks associated with PFAS. Their lobbying efforts have delayed stricter regulations and allowed continued production and use of these harmful substances [5] (Lerner, 2024).

•**The Industrial Age After WWI and WWII:** The post-World War II era, often referred to as the "Golden Age of Capitalism," saw rapid industrial growth and technological advancements. This period was marked by increased consumerism and the mass production of goods, including those containing PFAS. The economic boom led to the widespread use of synthetic chemicals without adequately considering their long-term environmental and health impacts [6] (Pruitt, 2020).

•**Lack of Risk Assessments:** For decades, the potential risks of PFAS were not adequately assessed. Regulatory frameworks lagged the rapid development and deployment of these chemicals. The lack of comprehensive risk assessments meant that PFAS were used extensively before their harmful effects were fully understood [7,8] (ATSDR, 2022; ITRC, 2023)

•**Cover-Ups of Scientific Data on Serious Long-term Health Effects:** For decades, major chemical companies were aware of the potential health risks associated with PFAS exposure but often prioritized profits over safety [9] (Balbuena et al., 2023). Internal documents from companies like DuPont have revealed that while they knew about the harmful effects of PFAS, they continued production, keeping the information hidden from the public. For example, there have been numerous instances where chemical companies suppressed scientific data on the health risks of PFAS. Internal documents from companies like 3M and DuPont revealed that they were aware of the dangers posed by PFAS as early as the 1960s but chose to conceal this information [5,10] (Lerner, 2024; Tullo, A., 2021) This cover-up has significantly delayed regulatory actions and public awareness [9] (Balbuena et al., 2023).

• **Current Litigation:** Numerous lawsuits against chemical companies for PFAS contamination exist. A landmark case was settled in 2017 when DuPont and its spin-off Chemours agreed to pay $671 million to resolve 3,550 personal injury claims linked to PFOA releases in Parkersburg, West Virginia. Similar litigations continue to emerge as states and municipalities seek damage reparations and funding for water treatment solutions [11] (Reed, 2019).

The unregulated growth of PFAS in consumer and industrial applications has not only resulted in long-term environmental contamination but also created new, emerging threats as research uncovers their interactions with microplastics.

1.2. The Nexus between PFAS and Microplastics: An Emerging Threat to Public Health and the Environment

As we continue to assess the environmental toll of PFAS, another critical issue has emerged: their interactions with microplastics, further complicating their environmental impact [12] (Smith et al., 2020).

Per- and polyfluoroalkyl substances (PFAS) and microplastics represent two significant environmental contaminants. While they have been studied individually, understanding their combined impact—the PFAS and microplastics nexus—is increasingly critical for public health, consumer awareness, and environmental sustainability [13] (Jones & Brown, 2021).

• **PFAS Persistent Environmental Pollutants:** PFAS are a group of synthetic chemicals extensively used in industrial processes and consumer products, including non-stick cookware, stain-resistant fabrics, and firefighting foams. They are highly resistant to degradation, earning them the moniker "forever chemicals" (EPA, 2024e). PFAS are known to contaminate water, air, and soil, and they accumulate in the human body, leading to potential adverse health effects such as cancer, immune system disorders, and endocrine disruption [14] (ATSDR, 2024).

• **Microplastics-Ubiquitous Contaminants:** Microplastics, which are plastic fragments smaller than 5 millimeters, originate primarily from the degradation of larger plastic materials and the microbeads commonly found in personal care items. These particles have become widespread, contaminating oceans, freshwater systems, and soil, with evidence of their presence in human tissues and organs [15] (NOAA, 2024). Microplastics can carry harmful chemicals, including PFAS, adsorbing them from the surrounding environment [16] (Bakir et al, 2012).

• **Interconnection Between PFAS and Microplastics:** Studies have revealed a critical interaction between microplastics and PFAS, where the former can act as carriers, helping PFAS move through and persist within different ecosystems [17] (Wang et al., 2015). The hydrophobic nature of microplastics enables them to absorb PFAS from contaminated water, leading to concentrated microplastics that act as new sources of PFAS pollution as they move through food webs [18] (Rochman et al, 2015). This sorption process can lead to bioaccumulation and biomagnification, where organisms at higher trophic levels, including humans, are exposed to increased levels of these harmful substances [19] (Fossi et al, 2016).

• **Public Health Implications:** The interaction between PFAS and microplastics poses severe public health concerns. Both contaminants are associated with a range of health issues. The presence of PFAS in microplastics can exacerbate their toxicity, leading to greater health risks upon ingestion or inhalation. This is particularly problematic in marine environments, where seafood consumption is a primary route of exposure to both microplastics and PFAS for humans [20] (Toms et al., 2009).

• **Environmental Impact:** The dual presence of PFAS and microplastics also brings heightened environmental challenges. PFAS-bound microplastics can disperse widely, affecting remote ecosystems and causing long-term environmental damage. They threaten wildlife, particularly

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aquatic organisms, by disrupting reproductive and hormonal systems and leading to physical harm from ingestion [21] (Teuten et al., 2009).

•**Consumer Awareness and Mitigation Strategies:** Raising consumer awareness about the sources and dangers of PFAS and microplastics is crucial. Individuals can reduce their exposure by avoiding products that contain these substances, such as certain cosmetics, non-stick cookware, and single-use plastics. Policy interventions, such as banning PFAS in consumer products and implementing stricter regulations on plastic use and disposal, are essential to mitigate this threat [22] (NOAA, 2024a).

1.3. The Human Cost of Decades of Delay, Cover-Ups, and Mismanagement of PFAS and Plastic Waste

The delayed response and mismanagement of PFAS and plastic waste have had severe human costs. Communities near manufacturing sites have experienced higher rates of cancer, thyroid disease, and other health issues linked to PFAS exposure. The economic burden of healthcare costs and environmental cleanup is staggering, with estimates running into trillions of dollars [23–25] (Merkl et al., 2022; MPCA, 2023; EPA, 2024).

The nexus between PFAS and microplastics represents a multifaceted environmental and public health challenge. As research continues to elucidate the complex interactions and impacts of these contaminants, informed policies and consumer practices are necessary to address the pervasive threat they pose to health and the environment.

2. PFAS and Long-Term Health Effects

While the environmental persistence of PFAS compounds raises substantial ecological concerns, their presence in the human body poses significant health risks, which have been increasingly documented in global health research.

Perfluorinated alkyl substances (PFAS) possess a fluorinated carbon chain of different lengths in partial or full form terminated by a carboxylate, or sulfonate i.e. a functional head group [26–28] (Ao et al., 2019; Cao et al., 2022; Jane et al., 2022). Six or more fluorinated carbon backbones belong to long-chain PFAS whereas less than six fluorinated carbons indicate the short-chain ones.

PFAS could induce reproductive toxicity, hepatotoxicity, and metabolic disorders [27–33] (Amstutz et al., 2022; Cao et al., 2022; Jane et al., 2022; Ojo et al., 2021; Solan et al., 2022; Xu et al., 2019, 2020) affecting the main organs such as blood, liver, and kidney.

The exposure of long-chain PFAS has been associated with the risk of cardiovascular disease, immune system disorder, and cholesterol metabolisms as indicated by epidemiological studies [34,35] (Donat-Vargas et al., 2019; Huang et al., 2018).

Hexafluoropropylene oxide-dimer acid (HFPO-DA), also known as GenX, constitutes a common short-chain PFAS alternative, replacing industrially PFOA, the linear long-chain perfluorooctanoic acid, representing most of the common PFAS, offering wide applications in manufacturing. These shorter-chain PFAS can accumulate in the human body and can be found everywhere [36–39] (Conley et al., 2021; Moro et al., 2022; Solan et al., 2023; Wen et al., 2020).

A concentration of serum PFOA and perfluorooctane-sulfonic acid (PFOS) up to 32 μg/mL and 118 μg/mL, respectively has been shown by occupationally exposed workers [30,40,41] (Ojo et al., 2021; Yang et al., 2023a, 2023b). The average half-life of serum PFAS, such as PFOA and PFOS, is evaluated to be in the range of 1–5 years. The reason for this long bio-accumulation and bio-persistence of the long-chain PFAS in the circulation system is the most abundant protein in the blood, albumin and its binding [40–50] (Alesio et al., 2022; Bangma et al., 2020; Beesoon and Martin, 2015; Chen et al., 2015; Chi et al., 2018; Crisalli et al., 2023; Jackson et al., 2021; Qin et al., 2010; Yang et al., 2023a, 2023b; Zhang et al., 2020).

Peng et al. [51] reported that the branched short-chain GenX could bind to bovine serum albumin (BSA) with a lower affinity compared to that of linear long-chain perfluorooctanoic acid (PFOA).

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Implications of PFAs affect children. Exposure of children to perfluorooctanoate (PFOA) is associated with a higher risk of developing asthma. Same for exposure to perfluorooctane sulfonate (PFOS) associated with impaired lung function as reported by Rafiee et al. [52].

A higher probability of exposure to PFAS appears in young children compared to adults due to their smaller size, higher respiratory rates, and behaviors related to hand-to-mouth, and crawling which required interactions with contaminated surfaces, such as floors [53] (Starnes et al., 2022). Inhalation; ingestion of dust, soil, food, water, and breastmilk; and dermal exposure to contaminated air or materials consist of some of the major routes of children's exposure to PFAS [54] (Haug et al., 2011).). Higher concentrations of PFAS in the serum of children compared to adults have also been reported [55,56] (Daly et al., 2018; Graber et al., 2019).

In the same context, Rocabois et al. [57] identified dose-response relationships for 50 substance-outcome pairs, corresponding to 20 chemicals and 17 health outcomes. PFAS could contribute to cardiovascular disease [58] (Schillemans et al. 2024).

Human-induced pluripotent stem cell (iPSC)-derived cardiomyocytes are employed widely for cardiotoxicity testing. A total of 56 PFAS from different subclasses were tested in concentration-response using human iPSC-derived cardiomyocytes from 16 donors without known heart disease. Ford et al. [59] reported that of the tested PFAS, 46 showed concentration-response effects in at least one phenotype and donor.

One of the most significant and highly persistent endocrine-disrupting chemicals (EDCs) with extremely high thermal and chemical stability are Perfluoroalkyl substances (PFAS) [60,61] (Cornelis et al., 2012; Stubleski et al., 2016). Exposure to endocrine-disrupting chemicals (EDCs) may modify the homeostasis of the endocrine system [62] (Sifakis et al., 2017) and cause the start and progression of endometriosis [63] (Smarr et al., 2016), which is affected by hormonal, genetic, immunological, lifestyle, and environmental factors [64] (Cousins et al., 2023). Exposure to certain PFAS may increase the odds of endometriosis as reported by de Haro-Romero et al. [65].

Multiple possible routes of exposure to PFAS exist, and these consist of the drinking water route and the diet [66–69] (Ghisi and Manzetti, 2019; Hammarstrand et al., 2021; Li et al., 2018; Rickard et al., 2022). PFAs have been detected in human placenta, breast milk, follicular fluid, and meconium samples [70–74] (Bjerve et al., 2012; Domínguez-Liste et al., 2024; Kim et al., 2020; Vela-Soria et al., 2020; Zheng et al., 2022). Highly detectable serum or plasma concentrations of PFAS, such as perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), and perfluorohexane sulfonate (PFHxS) have been found in pregnant women and children [74–79] (Fabelova et al., 2023; Freire et al., 2023; McAdam and Bell, 2023; Zheng et al., 2022; Richterova et al., 2023; Zhang et al., 2023).

In addition, a positive association between certain PFASs and periodontitis, which might be partially mediated by sex hormones (testosterone and the ratio of testosterone to estradiol) has been shown by Wu et al. [80].

2.1. PFAS Around the Globe and Risk Assessment

Different studies have been carried out in the States showing correlation of serum PFAS concentration with hyperlipidemia. In this study by Zhou et al. [81] (2024) data from the 2013–2016 National Health and Nutrition Examination Survey were analyzed for a total of 2665 adults taking into account participants' serum PFAS (perfluorooctanoic acid [PFOA], perfluorononaic acid, perfluorodecanoic acid, perfluoroundecanoic acid, perfluorohexane sulfonic acid, and perfluorooctane sulfonic acid).

In India, Koulini and Nambi [82] (2024) revealed PFAS levels up to 136.27 ng/L in both surface and groundwater samples from Chennai. The significant sources of contamination with PFAs turned out to be industrial emissions, untreated domestic wastewater discharge, and open dump sites. Hence, concerns are raised about potential risks to ecosystems and human well-being.

In Israel, Belmaker et al. [83] reported that there is likely no safe level of exposure to endocrine-disrupting chemicals (EDCs), with increasing evidence of trans-generational and epigenetic effects.

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They mentioned several existing Israeli laws to reduce plastic use and waste and suggested reinforcing the taxes on single-use plastic (SUP).

In Italy, Biggeri et al. [84] found an association of PFAS exposure with mortality from cardiovascular disease. They also showed evidence regarding kidney cancer and testicular cancer found to be consistent with previously reported data. The data came from the Italian National Institute of Health who pre-processed and made available anonymous data from the Italian National Institute of Statistics death certificate archives for residents of the provinces of Vicenza, Padua and Verona who died between 1980 and 2018 observing 51,621 deaths vs. 47,731 expected.

According to the European Food Safety Authority (EFSA), one of the most concerning health effects of PFAS exposure is the reduced antibody response to vaccines in young children. To address this, EFSA established a tolerable weekly intake (TWI) level of 4.4 ng per kilogram of body weight for the combined total of four major PFAS compounds—PFOA, PFOS, PFNA, and PFHxS—commonly found in human serum. [85] [EFSA, 2020].

PFAs risk assessment also includes modern computational tools, such as the Agent-Based Model (ABM) Universal Immune System Simulator (UISS) and Physiologically Based Kinetic (PBK) models serving as vital tools in chemical risk assessments, showing the interaction with the human immune system enabling the simulation of the host immune system's reactions to diverse stimuli and response to specific adverse health contexts [86] (Iulini et al. 2024).

2.2. *Scientific Research and Health Impacts in the United States of America*

Continued deep studies in the United States have confirmed the linked PFAS exposure to various health issues, including liver damage, thyroid disease, decreased fertility, high cholesterol, obesity, hormone suppression, and cancer. Academic research such as the C8 Science Panel, which studied the effects of PFOA (a type of PFAS) on communities near DuPont's Washington Works plant, confirmed the associations between PFAS exposure and several health conditions.

The National Health and Nutrition Examination Survey (NHANES) has measured PFAS levels in blood in the U.S. population since 1999. NHANES is a program of studies designed by the Centers for Disease Control and Prevention (CDC) to evaluate the health and nutrition of adults and children in the United States. NHANES data are publicly released in 2-year cycles [87] (ATSDR, 2024a).

As depicted in Figure 2 above:

- Since 2002, the manufacturing and consumption of PFOS and PFOA in the US have decreased.
- Reduced PFAS use has led to lower blood PFAS levels.
- Between 1999-2000 and 2017-2018, blood PFOS levels fell by more than 85%.
- Between 1999-2000 and 2017-2018, blood PFOA levels fell by more than 70%.
- As PFOS and PFOA are phased out and replaced, individuals may get exposed to additional PFAS. [88] (CDC, 2024)

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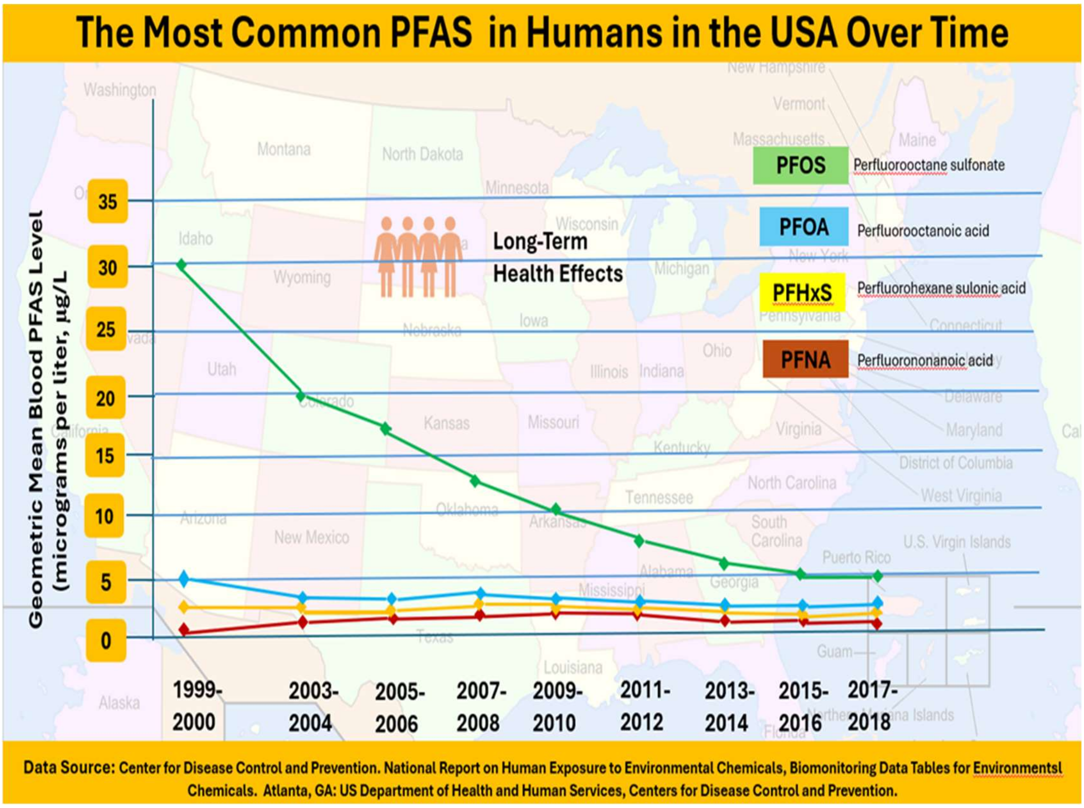

Figure 2. Blood Levels of Common PFAS in People U.S.A.

2.3. Center for Disease Control (CDC) PFAS Medical Studies and Guidelines

The CDC has conducted and supported various studies related to PFAS, focusing on health impacts.

Key findings and recommendations are included, as presented in Table 1.

Table 1. Center for Disease Control (CDC) PFAS Medical Studies and Guidelines [89–93] (ATSDR, 2016; CDC, 2024a, EPA 2024c; EPA 2024 d; ATSDR, 2024b).

Center for Disease Control (CDC) PFAS Medical Studies and Guideline	
The CDC has conducted and supported various studies related to PFAS, focusing on health impacts. Key findings include:	In response to the health hazards linked with PFAS, the CDC provides various guidelines:
Health Effects	**Preventive Measures**
Research reveals an association between PFAS exposure and a variety of health concerns, including immune system effects, hormonal disruption, and increased cholesterol levels. Studies have also suggested possible links to certain cancers, such as kidney and testicular cancer	The CDC advises limiting the use of products containing PFAS, especially for everyday items like water-resistant fabrics and non-stick cookware. Consumer education on identifying and avoiding PFAS products is critical
Biomonitoring	**Remediation Strategies**
The CDC's National Health and Nutrition Examination Survey (NHANES) has studied PFAS levels in the human population., providing essential data on exposure levels across the U.S. population	For contaminated sites, the CDC recommends various remediation strategies, including: •Activated Carbon Filtration: Effective in reducing PFAS concentrations in drinking water. • Ion Exchange Resins: Used to absorb PFAS from water supplies.

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	• High-Temperature Incineration: Identified as a method for breaking down PFAS in waste materials
Community Studies	
The CDC's Agency for Toxic Substances and Disease Registry (ATSDR) has undertaken health assessments in communities with potential PFAS pollution, allowing researchers to better understand localized health effects.	
Policy Recommendations	
The CDC calls for stricter regulations governing PFAS use and disposal, emphasizing the need for states and local entities to create water quality standards that reflect the most recent scientific findings regarding PFAS toxicity CDC Policy Recommendations for PFAS Regulation, 2020.	

3. PFAS Impact, Activities, and Studies Around the World

3.1. PFAS Levels in Food Products and Dietary Intake in Different Countries

In a general sense, most of the recent investigations have been performed in China, and European countries, only some of them being conducted in the USA and Australia.

- China:

Aquatic organisms, living in contaminated (artificial or natural) environments, are prone to accrue the pollutant exceeding water environment in which they live. In this line, PFAs may be transmitted from the contaminated water, food or suspended sediment with emphasis on the aquatic organism [94] (Starling et al., 2024). Wang et al. [95] (2021) examined the level and human exposure of ten linear PFASs, eight branched PFASs for PFOA, comprising NaDONA and HFPO-DA and PFOS, and four alternatives were characterized in animal-origin and vegetable dietary food samples consumed by Beijing populaces. In this study, PFASs occurrence and concentrations in fish (freshwater and marine) samples were superior to other food trials. In these samples, linear-PFASs were commonly found at 444 pg/g ww and 451 pg/g ww in marine and freshwater fish, respectively. As reported by the EDI findings, the residents occupying Beijing, which fish consumption was the dominate source of ∑PFOS and 6:2Cl-PFESA, were not meaningfully exposed to PFASs.

Via HPLC–MS/MS, Bao et al. [96] (2019) investigated the PFAS extent of contamination in numerous home gardens around the Fuxin fluorochemical industrial park (FIP), comprising groundwater from the public water systems and garden soils. In groundwater beneath the Fuxin FIP, the maximum levels of PFBS and PFOA were 21 and 2.5 μg/L, respectively. Furthermore, at 67–87% of the ΣPFAs-comprising PFBA and PFBS, were found to be the main pollutants in vegetables and eggs from the residential gardens around the FIP. In this regard, it was also established that PFBA could penetrate garden-produced fruits and vegetables through the application of local PFAs contaminated drinking water for irrigation [97] (Scher et al., 2018). These outcomes were confirmed by the high link between PFBA/PFOA/PFBS in local groundwater and those detected in home-produced vegetables.

Later, Bao et al. [98] controlled PFAS occurrence in groundwater and surface water on Fuxin FIP Liaoning Province - China. They reported the prevalence of PFBS and PFOA in the groundwater samples, with the relative abundance of these compounds to be 24 - 25 times greater than that stated by the same authors in 2009 [99] (Bao et al., 2011). Bao et al. [98] (2020) reported that PFBA, PFOA, and PFBS were the main PFAS in soil greenhouse samples (~ 6.1, 6.8, and 46 ng/g), tomato (~ 87, 1.7, and 13 ng/g), and cucumber (~63, 2.6, and 15 ng/g), showing connection with those in groundwater samples, signifying PFAS contaminations could be present into soil and vegetables in the greenhouse throughout long-term groundwater irrigation. In addition, these authors detected high bioaccumulation efficiencies (BAFs) of short-chain PFAS in vegetables. As an illustration, BAFs of shorter-chain PFASs in greenhouse cucumbers and tomatoes were beyond of longer-chain PFASs. To this point, via daily consumption, the contact to PFBA, PFOA and PFBS in cucumber tomato and from local greenhouse might not provoke a health risk for the residents living near the FIP. Another

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study was conducted in Hangzhou City-Zhejiang Province-China close to a landfill. The ΣPFAs-levels in the groundwater samples ranged between 17.3-163 ng/L, and, the greatest plentiful element was PFBA, succeeded by PFOA, PFPeA, PFHxA, and PFHpA. The authors concluded that the landfill leach did not cause groundwater contamination, demonstrating a low risk for human health [100] (Xu et al., 2021). In other spots like the Hubei - China, mutable concentrations of 12 diverse PFASs have been sensed in the Qing River, with concentrations peeking through summer in an extent from 39-207ng/L [101] (Zhou et al., 2017). Another study was carried out on the river–lake system on the Yangtze River in Jiangxi Province, and an occurrence of eleven PFAs types in the surface waters was detected. This prevalence seemingly originated from the municipal waste-water treatment plants (WWTPs). High levels of ΣPFAs in the surface waters of the Nanchang City urban area (146-586 ng/L) and the Jiujiang section of the Yangtze River (46-157.6 ng/L) were detected with a pronounced occurrence of PFBS and PFOA [102] (Tan et al., 2018). A quantitative analysis of C3-C14 PFAS in the marine and fluvial sediment samples from fluviomarine and coastal areas of the East China Sea was carried out by Yan et al. [103] (2015). The average ΣPFAs was 9 g/g dw with the highest occurrence shown by PFOS, PFHpA and PFOA [103] (Yan et al., 2015). Yao et al. [104] (2014) conducted a local scale examination on 2 industrial towns in the North China for the evaluation of the PFAS concentrations in the surface rivers and nearby groundwater. In all investigated four rivers in the two cities, PFCAs class caused over 70% of the detected PFASs. The leading PFCA was PFOA ranging between 8.6 and 20 ng/L in Tianjin and 6.37–26 ng/L in Weifang, respectively. Samples from Dagu Drainage Canal (Dagu) in Tianjin showed the uppermost concentration. Those short-chain PFASs (C4–C6) were detected at a comparable level of the longer-chain PFASs (>C6), with PFBA to be leading in the short-chain equivalents. This designates an association between an increasing input of short-chain PFASs and industrial discharges or wastewater treatment plant effluent, which could be due to the switching of manufacturing to short-chain products [104] (Yao et al., 2014).

In Bohai Sea, Kwok et al. [105] (2015) investigated the occurrence of short-chain and long-chain PFAS at low-water and high-water phases surface water. The overall concentration of PFAS in seawater was either undetectable or at 99ng/L. PFOA was the predominant analyte in water samples with high levels of PFBS, PFHxS and PFOS, detected unveiling chronological differences in the sole water samples. This fact indicated that the difference in seasonal activity characterized the sources of PFAS emission into Bohai Sea. In 2017, Chen et al., assessed the PFAS levels in coastal wastewater and river water in the Bohai Sea. In the river water samples, PFBS, PFOA and PFOS were the principal detected compounds, with ΣPFAs ranging from 13-70ng/L indicating the existence of sites with weighty contamination. On the other hand, PFOA was the most signified substance in coastal wastewater, wherein ΣPFAs levels were ranged between 16.7-7522 ng/L, and 13-319 ng/L, respectively. The authors indicated the effect of riverine playing a key role in PFAS pollution of the Bohai Sea, with the release of coastal wastewater leading to a smaller effect [106] (Chen et al., 2017).

In the Xiamen Sea area (China), the bioconcentration (BCFs), ranged from 6400–9700 L/kg to 3300–8000 L/kg for PFOA and PFOS, respectively [107] (Dai and Zeng, 2019) reflecting the quantity of PFAAs in diverse trophic levels of aquatic animals. In the wild crucian carp, collected from Yubei River (China), log10BAF was 3 (in muscle) and 4 (in blood) [108] (Lee et al., 2020). Cui et al., [109] (2019) analyzed 35 different PFAS in Ruditapes philippinarum, and confirmed that the bioaccumulation factors (lg BAFs) were associated to C chain length, and the biota-sediment accumulation factors (lg BSAFs) lessened with a C chain length (C8-C13).

In the Xiamen Sea, Kelp algae concentrations ranged between 1.6 and 4.6, 1.4–3.6 and 8-13 ng/g, for PFOA, PFOS, and ΣPFAs, respectively [107] (Dai and Zeng, 2019). *Salvinia natans Ceratophyllum demersum* L., and *Hydrocharis dubia* (Bl.) Backer floating plants collected from Baiyangdian Lake (China), presented high levels of ΣPFAs (≈19.2 ng/g) with a marked occurrence of PFOA (≈10.4 ng/g) and PFNA (≈20.1 ng/g). However, PFHpA, PFBS, PFHxS were not detected [110] (Shi et al., 2012). In Jiaozhou bay coast, 35 PFAS were detected in Ruditapes philippinarum samples, found to be equal to 15–27 μg/kg [109] (Cui et al., 2019).

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23 PFCs were detected in molluscs from a semi-closed basin of the Bohai, displaying a variation between aquaculture sites with the PFOA being the most detectable (87% of the ΣPFAs) followed by PFNA, PFDS and PFOS [111] (Guo et al., 2019). These authors confirmed that molluscs sampled in the various mussel farming exhibit the highest levels of contamination in samples taken near industrial areas [111] (Guo et al., 2019). One of the general factors with a significant impact in biota contamination is linked to geographical origin of the analyzed organisms. It is confirmed that PFAs concentrations of organisms trapped in waters, touched by anthropogenic pollution, are normally higher than levels in organisms from open oceans [111] (Guo et al., 2019).

Collected from agricultural parks in China, Li et al. [112] (2019) analyzed 21 PFAs on vegetables and fruits which are collected from Changshu fluorine-chemical industrial park (CFCIP). The ΣPFAs are 11.5 and 10.5 ng/g for vegetables and fruits, respectively. In terms of detection frequency and concentrations: PFOA and PFBA are the dominant classes of PFAs. In this line, PFOA abundance was assessed at 35.5% in vegetable and fruit samples. The predominant presence of PFBA in agricultural products might be clarified by the high transfer factor of PFBA from nutritional matrix to aerial tissues of the plant [113] (Jin et al., 2024). Long chained PFCAs were occasionally noticed in a few selection sites with DF less than 7%. Qian et al. [114] (2023) indicated that long-chained PFCAs might accumulate in the root part. In addition, simultaneous bioaccumulation of PFBA and PFOA was found in melons and solanaceous species and pears. Moreover, grapes and leafy vegetables exhibited a bioaccumulation of PFOA and PFBA at high levels.

In a previous study conducted by these authors in 2017, Liu et al. revealed a linear positive link between the prevalence of PFCAs in agricultural land soil near an FCIP and the PFCAs bioaccumulation of in maize grains and wheat. These authors noticed that the chief PFAS found in agricultural soils, groundwater and crops come from the effluent discharges from the FIP. Despite the dominance of PFOA in the soil matrix, short-chain PFCAs (PFBA), presented the maximum levels in multiple crops due to bioaccumulation preferences [115,116] (Liu et al. 2017, 2019). A few investigations were conducted on vegetables sold at supermarkets and retail stores. A detection frequency of PFBS at 12.5% of the time with a mean concentration of 0.027 ng/g was shown in a supermarket survey in Beijing [95] (Wang et al. 2021). That is why tracking of PFAS exposure and loading at the diverse steps of the supply chain, along with an improvement of the traceability system is imperative.

Bao et al. [96] (2019) reported that ΣPFAs extended from 63 to 108 ng/g at home-produced whole eggs. This fluctuation depends on the remoteness (between 0.2 to 1.0 km) from FIP Park in China. Same findings were reported by Zafeiraki et al. [117] (2016). These authors concluded that the home-produced eggs were more adulterated than commercially ones. This is probably due to the controlled feed and environment of neighboring hens for large-scale egg production. Home-grown chicks are more prone to feed and roam on zones that may have been topic to outside contamination.

- European Countries:

Zafeiraki et al. [118] (2019) analyzed PFAs in fish samples, bivalves, crustaceans, and eel captured from Dutch waters, or purchased from markets. ΣPFAs levels were highest in eels and shrimps which are taken from rivers and lakes, and the Dutch coast, respectively. The majority of the farmed studied fish have a ΣPFAs ranged between 0.06-1.5 ng/g. Geographically, levels in marine fish from the northern North Sea were inferior to those registered in the central and southern North Sea (e.g. flatfish and cod). Regarding eel, no considerable geographical changes were established. The contamination order was comparable in all species, and PFOS and other long-chain PFASs were commonly detected, whereas, short-chain PFASs were infrequently detected. Remarkably, the major part of detected PFOS concentrations in eels (~93%) and one shrimp sample surpassed the EU Environmental Quality Standard (EQS) for surface water of 9.1 µg/kg. in this investigation, Zafeiraki et al. [118] (2019) detected PFOS concentrations at a range:3.3-67ng/g, and these findings were reliable with previous studies on eels collected from the Netherlands and other European countries. According to Kwadijk et al. [119] (2010), PFOS in eel from Dutch rivers ranged from 7-58 ng/g in eel muscle. Comparable PFOS concentrations were also reported in eels collected from the river Mohne

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in Germany (37-83 ng/g) [120] (Holzer et al., 2011) and from the Loire estuary in France (18-39 ng/g) [121] (Couderc et al., 2015). In contrast, lower PFOS levels were found in eel muscle tissues from Italy (0.3-2.48 ng/g) [122] (Giari et al., 2015) and Spain (highest 21.6 ng/g ww) [123] (Pignotti et al., 2017). On the other hand, low ΣPFAs concentrations and PFOS have been examined previously in mussels from Spain [124] (Zalabeta et al., 2015), France [125] (Munschy et al., 2015), Greece [126] (Vassiliadou et al., 2015), Denmark [127] (Bossi et al., 2008) and the Mediterranean Sea [128] (Nania et al., 2009). In a study conducted by Schmidt et al. [129] (2019), four PFAS were detected in the Rhone River from 2017 to 2018. In this investigation, high ΣPFAs are ranging from 13 to 200 ng/L, high levels of PFHxA (8–193 ng/L) and PFOS beyond the annual average EQS in more than 80% of the cases. On the study of Squadrone et al. [130] (2015), a substantial correlation between weight and PFOS levels in the European perch (*Perca fluviatilis* L.) from Lake Varese, Italy.

- USA and Australia:

Houtz et al. [131] (2013) analyzed groundwater samples from Ellsworth Air Force Base in South Dakota, USA. The middle levels of PFOS and PFOA were 19,000 and 26,000 ng/L, respectively. In addition, higher levels were detected for PFHxS and PFHxA at 71,000 and 36,000 ng/L, respectively. Braunig et al. [132] examined several biological and environmental matrices sampled from Oakey (Australia). PFOS (4300 ng/L) was the most abundant compound, followed by PFHxS (2300 ng/L) detecting higher concentrations in the groundwater. PFAAs were detected in over 50% of the water samples comprising of PFOA, PFPA, PFHxA and PFBS and were found at levels between 120-600 ng/L. Allinson et al. [133] (2019) elucidated 18 PFAS substances, including PFBS, PFOA, PFBA, PFHxS and PFOS at 7, 8.5, 11, 42, 75 ng/L, respectively by examination of the occurrence of common PFAS in surface waters from 7 estuaries and creeks.

Consequently, a summary of the PFAS, their corresponding classes, and levels found in various food products sampled in different countries is described in Table 2 where PFAS Concentration in Food and Dietary Intake in a number of countries is shown.

Table 2. PFAS Concentrations in Food and Dietary Intake in a Number of Countries.

Country	Food products samples	Origin	Assessed PFAS	Method of determination	Findings	Total PFAs	References
Freshwater products							
China	16 Fish sample, 25 meat samples, 3 egg samples 72 vegetable samples	Supermarket	22 PFASs	UPLC-TQS	-Linear-PFASs and PFBS were frequently identified in fish and vegetables, respectively - The EDI < tolerable weekly intake as recommended by EFSA	168 pg/kg bw 54 47 46	[95] Wang et al., 2021
European subalpine area	Fish (fillets, liver, viscera and carcasses)	Wild	11 PFASs	LC-MS-MS	In lake, PFAS in fish is linked with the level of the urbanization of the lake catchment	0.85-13.8 ng/g 13.5-36.9 11.5-59.0 3.8-31	[134] Valsecchi et al., 2021
Italy	red deer, roe deer, chamois and wild boar	Wild	16 PFASs	LC-HRMS Orbitrap	PFASs only in wild boar species	0.83-2.90 ng/g	[135] Arioli et al., 2019
Italy	Wild boar	Farm animals	33 PFASs	LC-Q-Orbitrap	18 PFASs were assessed at level > 0.2 ng/g	-	[136] Barola et al., 2020

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China	Vegetable Whole egg Egg white Egg yolk	fluorochemical industrial park	10 PFASs	HPLC–MS/M	PFBA and PFBS were the major contaminants in both home-produced vegetables and eggs	1.7-87 63-108 43-58 106-146	[96] Bao et al., 2019
USA	Fish fillet Mullet Spot Croaker Red Drum Seatrou	Estuary	11 PFASs	LC-MS/MS	-PFAS levels in fillets changed by location -In certain species and locations PFOS levels surpassed human screening standards for cancer risk	12.4-12.7 ng/g 28.4-33 19.5-28.4 27-29.6 23.4-31.1	[137] Fair et al., 2019
Netherlands	22 bivalves, crustaceans, marine and farmed fish.	wild and farmed aquatic animals	16 PFASs	LC-MS/MS	PFAS levels in eel> bivalves and crustaceans > marine fish > farmed fish	0.06 -172 ng/g	[118] Zafeiraki et al., 2019
Sweden	Liver of Killer whales Harbor seals Ringed seals	Seawater	36 PFASs	UPLC-MS/MS and UPLC-Orbitrap-MS	-PFOS dominated in all but one Icelandic and 3 US samples, where the 7:3 FTCA) was predominant.	614 ng/g 640 536	[138] Spaan et al., 2020
China	Soft tissues of Shell fish	Seawater	35 PFASs	LC-MS/MS	-Bioaccumulation factors (lg BAFs) were linked with C chain length, -lg BSAFs (biota-sediment accumulation factors) diminished with a growth in C chain length (C8-C13).	15.5–27.5 ng/g	[109] Cui et al., 2019
China	Chameleon goby Muscle Grass carp muscle Ghost crab soft tissues Hermit crab soft tissues Oyster soft tissues	Seawater and Freshwater	6 PFASs	LC-MS/MS	PFA in water is highly positive connected with the PFA concentration in sediments	10.97–12.93 ng/g 8.87–10.66 7.8–10.47 7.73–8.06 12.45–12.76	[107] Dai, & Zeng 2019
China	Fish (Sea bream, Pagrosomus major) samples	Seawater	11 PFASs	UHPLC-MS/MS	PFOS was the main compound that was detected at 0.13 ng/g	0.04–2.14 ng/g	[139] Gao et al., 2018
Sweden	Liver of Baltic cod	Seawater	28 PFASs	UHPLC-MS/MS	Significant negative correlations were assessed between PFASs and liver somatic index.	6.03–23.9 ng/g	[140] Schultes et al., 2020

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					-body length was negatively correlated with PFOA and PFNA, and positively linked to PFDoDA and FOSA		
Greece	Giant devil ray (Muscle and gills) Smalltooth sand tiger (Muscle and gills) Smalltooth sand tiger (gills and liver)	Seawater	15 PFASs	LC-MS/MS	PFTrDA was the most predominant compound in terms of concentration and frequency of detection, followed by PFUnDA and PFOS	1.5–4.4 ng/g 1.5–4.4 62.2–65.4	[118] Zafeiraki et al., 2019
USA	Whole fish Atlantic croaker Red drum Spot Spotted seatrout Striped mullet	Seawater	15 PFASs	LC-MS/MS	Low PFAS levels in mullet and highest in croaker, spot, red drum, seatrout, and flounder. PFOS levels surpassed wildlife protective guidelines in 83% of whole fish.	15.2–21.3 11.3-66.1 14.7–67.8 17.3–85.4 6.2-20.7	[137] Fair et al., 2019
China	Liver, Muscle fish Yellow croaker Mandarin fish Crucian Carp	Freshwater	8 PFASs	UPLC–MS/MS	The calculated hazard ratio (HR) values designate no risk to human health if the amount of fish consumption was less than 14.35 kg ww (2.87 kg dw/ person/ year).	8.99–87.9 3.02–51.2 3.15–4.09	[141] He et al., 2015
Agricultural products							
China	shoot vegetables fruit/ vegetables flower vegetables root vegetables grain crops	Agricultural field	12 PFASs	LC-MS/MS	Vegetables and grains possess bioaccumulation preference to shorter-chain PFASs. -Vegetables showed highest BAFs of ∑PFASs in multiple crops.	~2355 ng/g ~1115 ng/g ~410 ng/g ~333 ng/g ~580 ng/g	[116] Liu et al., 2019
China	Fruit, shoot/stem, mushroom (leek, cucumber, eggplant, lettuce and tomato)	Greenhouse	20 PFASs	UPLC-MS-MS	PFOA was detected most frequently at 0.023 - 0.153 mg/ kg -Total PFAS levels extended - 0 to 0.683 mg/kg	(0 – 0.68ng/g)	[142] Zhou et al., 2019
China	Fruit	Greenhouse	8 PFASs	HPLC–MS/MS	Bioaccumulation efficiencies for PFAS from soil to	~ 93.5 ng/g	[98] Bao et al., 2020

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					vegetables were negatively related with the C chain length in PFASs.		
China	Fruit and shoots of Tomato, cucumber, eggplant, pepper, Chinese cabbage	Home gardens	10 PFASs	HPLC–MS/MS	PFAs might be recognized to the irrigation with groundwater from local public water systems	1.7-78 ng/g	[96] Bao et al., 2019
China	21 species	Agricultural field	21 PFASs	HPLC–MS/MS	Short-chain (C ≤ 8) PFCAs was presented in 97.1% of all samples	0.3-11.5 ng/g	[143] Li et al., 2019
Uganda	Yam (root) Maize (grain) Sugarcane (Shoot/stem)	Wetland Lake	26 PFASs	LC–MS/MS	PFAss concentrations < those reported in neighboring countries (e.g. Kenya) and industrialized countries (e.g. Germany and USA).	0.36 ng/g 0.2 ng/g 0.35 ng/g	[144] Dalahmeh et al., 2018
Meat and livestock							
Benin, Cameroon, Mali and Nigeria	Cooked beef	NA	14 PFASs	LC–MS/MS	PFAss concentrations equivalent or < in previous international Total Diet Study (TDS)	0.4 – 12.05 ng/g	[145] Vaccher et al., 2020
China	Pork Pork liver Chicken Duck Beef Egg	Supermarket	19 PFASs	LC–MS/MS	Linear-PFASs and PFBS were mainly found in fish and vegetables, respectively	0.02 ng/g 0.4 ng/g 0.026 ng/g 0.25 ng/g 0.04 ng/g 0.03 ng/g	[95] Wang et al., 2021
Italy	Meat Chamois Red deer Roe deer Wild boar	Wild	16 PFASs	GC-MS/MS and UHPLC-MS/MS	-FOS were noticed in 25% of the wild boar samples with very low levels.	- - - 0.83 – 2.90 ng/g	[135] Arioli et al., 2019
China	Egg Whole egg Egg white Egg yolk	Home-produced	10 PFASs	HPLC–MS/MS	-PFBA was the dominant PFAS contaminant in whole eggs - PFBS and PFOA contributed 31% and 24% of the whole PFASs, respectively	58 ng/g 146 ng/g 108 ng/g	[96] Bao et al., 2019

Greece	Beef Pork Chicken Sheep Milk Eggs	Production sites	2 PFASs	LC-MS/MS	Weekly intake values < the acceptable weekly intake proposed by EFSA	0.90 ng/g - 1 ng/g 1.75 ng/g 0.1 ng/g 0.81 ng/g	[146] Kedikoglou et al., 2019
Denmark	Meat of Harbor seals	Wild	15 PFASs	HPLC–MS/MS	PFASs were non-significantly higher in sub adults than in adults	17.2 – 21.8 ng/g	[147] Sonne et al., 2019

3.2. PFAS in Drinking Water and Food: Risks, Mitigation, and Regulatory Needs

PFAS (per- and polyfluoroalkyl substances) constitute a category of synthetic chemicals extensively utilized across multiple industries for their water- and grease-repellent characteristics [148] (EPA, 2024a). Nonetheless, they exhibit persistence in both the environment and the human body, resulting in significant apprehensions regarding their presence in potable water [149] (EPA, 2024b). Details, encapsulated in Table 3, delineate the principal risks linked to PFAS chemical contamination in drinking water, water treatment, and food products [150] (FDA, 2024). The necessity for effective mitigation strategies and the significance of rigorous regulatory measures to safeguard public health is critical [92] (EPA, 2024d).

Table 3. PFAS in Drinking Water and Food.

Supplies	Contaminant Sources	Risks, Exposure	Mitigation	Areas of Concerns	Regulatory Needs
Water: **Drinking Potable**	•Chemical Waste •Landfill leaching •Farmland sludge •Plastic islands	•Public Health •Soil Health •Agri-Food Systems •Cattle & Poultry •Food Processing	• Rapid Tests Rapid PFAS test kits would be ideal for the food industry and home use, improving monitoring capabilities at critical points.	• Lack of funding and resources for the widespread implementation of PFAS testing, mitigation, and bioremediation in the food industry and water processing and treatment sites.	•EPA Final PFAS National Primary Drinking Water Regulation, April 2024 https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas
Food Products	•Food Contact Materials	•Health Effects-Risks: ‣Endocrine disruptors, ‣Carcinogens, ‣Gastrointestinal disorders ‣Neurological disorders •Developmental disorders: Due to children's developing bodies, they are especially susceptible to chemical contaminants.	•Safer Packaging Alternatives:	•A primary concern is the persistent utilization of detrimental chemicals in food packaging. BPA and PFAS continue to be extensively utilized despite their recognized hazards. Studies indicate that alternative materials, including glass and polyethylene terephthalate (PET), can reduce the transfer of hazardous chemicals into food. Nevertheless, extensive implementation of these materials will necessitate substantial alterations in manufacturing methodologies and consumer habits.	• Stricter Regulations: Global regulatory agencies have enacted numerous regulations to restrict chemical contamination in food. The European Food Safety Authority (EFSA) has established tolerable daily intake (TDI) thresholds for numerous hazardous substances. However, these policies vary significantly between areas, with developing countries generally having less comprehensive regulatory frameworks. This inequality in enforcement puts some populations at risk of being

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	exposed to unsafe quantities of pollutants.

Sources: [92,149–161] EPA, 2024b; FDA, 2024; EPA, 2024d;CDC, 2024b; EPA, 2024e; Folorunsho et al., 2024; Lee, J.C. et al., 2023; Marandi, 2021; Matamoros, et al., 2019; Minet et al., 2022; Phelps et al.,2024: Onyeaka et al., 2024; Ottaway et al., 2021; Seltenrich, 2020.

• Due to its persistence, bioaccumulation potential, and related health risks, PFAS contamination in drinking water poses a substantial public health challenge [90,152] (EPA, 2024e; CDC, 2024a). Although initiatives to regulate and alleviate PFAS contamination are in progress, enhancing these efforts and allocating resources to advanced technologies and research is essential [92] (EPA, 2024d). Guaranteeing safe drinking water is a fundamental right, and mitigating PFAS contamination is critical to realizing this objective for all communities [162] (EPA, 2024f).

• Chemical contaminants in food pose a significant and escalating risk to human health. The enduring presence of pollutants such as PFAS, heavy metals, and endocrine disruptors, coupled with inadequate regulatory frameworks in certain areas, complicates the resolution of this issue [163–165] (FDA, 2024b; EHN, 2022; EFSA, 2024a). A global initiative is necessary to safeguard consumers, encompassing enhanced regulations, technological innovations, and public awareness campaigns [166,167] (WHO, 2022; FDA, 2024a). By reducing exposure to hazardous chemicals and implementing more sustainable agricultural practices, we can mitigate health risks associated with chemical contaminants and progress toward a safer and more sustainable future in food production [154,168,169] (NIFA, 2024; Britannica, 2024; Lee et al., 2023).

• Technological Innovations: Advancements in food technology, including enhanced detection methods for chemical contaminants and novel processing techniques, can mitigate contamination risks [170,171] (Forbes, 2023; CIFS, 2021). Enhanced filtration systems for irrigation water and innovative agricultural practices that minimize pesticide usage can reduce contaminant levels in crops [172] (FAO, 2022).

• Consumer Awareness: Public awareness is essential. Consumers should be informed of the risks associated with certain food packaging and encouraged to limit their exposure by choosing safer alternatives [150] (FDA, 2024). Furthermore, focusing more on home-cooked meals with fresh ingredients helps reduce exposure to toxins found in processed and fast foods [173] (WHO, 2024).

• Global Regulatory Harmonization: Governments and international organizations must collaborate to align safety standards and regulations, ensuring uniform protection across borders, especially for vulnerable populations in developing nations [173,174] (WHO, 2024; GHI, 2025).

•Research and Development: It is essential to prioritize investment in research to create safer alternatives to hazardous food packaging materials, including PFAS and BPA [172,175] (FSIS, 2024; FAO, 2022).

•Enhanced Surveillance Systems: Augmented monitoring and testing of food products throughout the supply chain can facilitate early detection of contamination and avert the distribution of hazardous products to consumers [173,176] (WHO, 2024; CDC, 2024).

•Public Health Campaigns: Enhanced public education regarding the hazards of chemical contaminants in food and methods for their avoidance should constitute a comprehensive strategy to mitigate consumer risk [176,177] (CDC, 2024; WHO, 2024a).

In conclusion, the pervasive presence of PFAS contamination in food and drinking water presents a significant public health challenge. These chemicals' persistence and bioaccumulation potential underscore the urgent need for stringent regulations, continuous monitoring, and innovative remediation strategies. By addressing PFAS contamination, we can protect ecosystems and ensure safer consumption of food and water for future generations [178] (Harvard, 2023).

3.3. Chemical Contaminants in Food and Their Impact on Health and Safety

As we pivot from the issue of PFAS contamination, it's essential to broaden our focus to the myriads of chemicals found in our food. From pesticides and additives to packaging materials, the journey from farm to table involves exposure to various substances. Understanding their impacts, regulatory frameworks, and safety measures is crucial for safeguarding public health and maintaining food integrity.

Food contaminated with chemicals has become a global health issue, presenting risks from mild gastrointestinal ailments to serious long-term conditions, such as cancer and developmental disorders [173] (WHO, 2024). The escalation of industrialization, globalization, and evolving agricultural methods has intensified these risks, rendering chemical contaminants a pressing concern for regulators and the food sector [167,179] (FAO, 2019; FDA, 2024a). This study offers a comprehensive analysis of the principal findings from various studies and articles regarding chemical contaminants in food, encompassing the sources of contamination, its effects on human health, and the requisite measures for prevention [180] (EFSA, 2024). Significant attention is directed towards per- and polyfluoroalkyl substances (PFAS), Bisphenol-A (BPA), and other harmful compounds that leach from packaging into food [163,181,182] (FDA, 2024b, d; Consumer Reports, 2022).

Despite initiatives to eliminate long-chain PFAS like perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), shorter-chain PFAS have emerged as substitutes in numerous products [183] (EPA, 2024). Research indicates that although these shorter-chain PFAS are less bio-accumulative, they still present considerable risks to human health, including hepatic damage, immune system suppression, and developmental disorders [164,181] (FDA, 2024d; EHN, 2022).

Furthermore, chemical contaminants in food pose a significant and escalating risk to human health. The enduring presence of pollutants such as PFAS, heavy metals, and endocrine disruptors, coupled with inadequate regulatory frameworks in certain areas, complicates the resolution of this issue [167,180,184] (FDA, 2024a; EHN, 2022a; EFSA, 2024). A global initiative is necessary to safeguard consumers, encompassing enhanced regulations, technological innovations, and public awareness campaigns [163,166] (WHO, 2022; FDA, 2024b). By reducing exposure to hazardous chemicals and implementing more sustainable agricultural practices, we can mitigate health risks associated with chemical contaminants and progress toward a safer and more sustainable future in food production [168,169] (NIFA, 2024; Britannica, 2024).

4. PFAS Impact and Activities Briefings: Regions Around the World

The impact and activities surrounding PFAS (per- and polyfluoroalkyl substances) vary significantly across regions worldwide. Each briefing in this section serves as a standalone report, meticulously crafted to raise awareness, educate the public, and address the multifaceted elements of the global PFAS crisis within the context of the specific region. By delving into regional nuances, these briefings aim give a full grasp of the effects of PFAS contamination on ecosystems, human health, and regulatory landscapes around the globe.

4.1. AUSTRALIA Briefing: PFAS Impact and Activities

In Australia, PFAS contamination has been strongly linked to the use of firefighting foams, particularly at locations such as airports, military bases, and training facilities. While firefighting foams for bushfires ('Class A') do not include PFAS, foams used for liquid fuel fires ('Class B') remain a significant source of pollution [185] (Australian Government, 2024). PFAS compounds are highly resistant to degradation due to their strong carbon-fluorine bonds, which contribute to their persistence in the environment (NIEH, n.d.). These substances are highly soluble in water, allowing them to easily leach from soil to water sources, enter the food chain, and cause contamination [186,187] (National Chemicals Working Group of the Heads of EPAs Australia and New Zealand, 2020; Willis and Connick, 2024).

PFAS pollution poses major environmental and health problems because of its persistence and potential for bioaccumulation. [187,188] (Willis and Connick, 2024; Shah and Oluto, 2024). These chemicals are internationally recognized as toxic to humans and wildlife and are being phased out in many countries, including Australia. PFAS contamination has been detected in soil, surface water, and groundwater across various locations, with most Australians having measurable levels of PFAS in their blood [185] (Australian Government, 2024).

The Expert Health Panel on PFAS in Australia has found limited scientific evidence in humans, with generally small health effects reported. However, there is a link between PFAS exposure and elevated blood cholesterol, kidney health issues, specific cancers, and vaccine responses [185,189] (Australian Government, 2024; Kirk et al., 2018). PFAS exposure in Australia is linked to cancer risks, reproductive health concerns, and environmental contamination [190–192] (Taylor, 2018; Warwick et al., 2024; Gregory, 2024). This underscores the need for continued monitoring and research to understand long-term health impacts.

The Australian government adopts a precautionary approach to controlling PFAS contamination, seeking to prevent or decrease exposure and considers new evidence to support positive health outcomes. This includes health-based guidance values, Australian drinking water guidelines, research initiatives, and PFAS biomarker testing [185] (Australian Government, 2024).

New South Wales Health is assisting water suppliers to test for PFAS due to increasing evidence of widespread contamination beyond Defense Force bases and airports (Gregory, 2024). The US EPA considers PFAS in drinking water unsafe, but Australian guidelines state a safe level of exposure is 0.07 μg/L, and Victoria regularly monitors drinking water for PFAS contamination [193] (NHMRC, 2022).

A Melbourne study found PFAS in groundwater samples near recycled water irrigation sites, raising concerns about potential drinking water contamination (Szabo et al., 2018). A national study found PFOS and PFOA in about half of the tested samples, underscoring the need for ongoing testing for public health and safety [133,185] (Allinson et al., 2019; Australian Government, 2024). Despite this, no maximum limits for PFAS contaminants in food have been set by Australian regulators or internationally [194] (FSANZ, 2022). FSANZ has developed non-regulatory "trigger points" for livestock products, seafood, fruits, and vegetables [194] (FSANZ, 2022).

A study in Australia discovered that perfluorinated alkyl acids (PFAAs) are persistent environmental contaminants observed in human serum and water treatment systems. The study assessed PFAA exposure via potable water, finding PFOS and PFOA among the most detected contaminants, with drinking water contributing 2–3% of the total exposure, reaching up to 22% and 24%, respectively [195] (Thompson et al., 2011).

PFAS poses significant risks to marine life through bioaccumulation, toxicity, and biomagnification, impacting ecosystems [188] (Shah and Oluto, 2024). A study found PFOS in eight of nine platypus livers, raising health concerns, while the only captive platypus had no detectable PFOS [191] (Warwick et al., 2024). Australian freshwater fish and crustaceans, such as common carp and Murray cod, show PFOS concentrations above the Australian trigger value, with variations due to foraging habits; more research is needed on their toxicological and reproductive effects [190] (Taylor, 2018).

PFOS accumulates in bottlenose dolphin livers, posing health risks to marine mammals [196] (Sciancalepore et al., 2021). PFOS and PFOA are toxic to sea urchins, mussels, and shrimp, affecting their development and survival [197] (Hayman et al., 2021). PFAS levels are higher in Australian sea lion, Australian fur seal, and long-nosed fur seal pups in urbanized areas near direct sources like defense bases and airports, with the highest PFOS in A. p. doriferus pups [198] (Taylor et al., 2021). PFAS compounds accumulate in marine food webs, raising ecological concerns for marine ecosystems and human consumers [199] (Du et al., 2020).

‣**Impact on Livestock:** PFAS are accumulating in livestock due to their migration onto agricultural properties. The environmental factors causing this accumulation are poorly understood, which limits management of livestock exposure and PFAS transfer through the food chain. Seasonal trends in PFAS body burden are linked to grazing behaviors and physiological water requirements.

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In Victoria, the impact on animals is low, reducing community exposure through meat produce [200] (Mikkonen et al., 2023).

‣**PFAS Handling and Disposal to Landfill:** Australia has guidelines for handling and disposing of PFAS, but stronger enforcement and industry cooperation are needed [201–203] (Coggan et al., 2019; Hepburn et al., 2019; Hall et al., 2021). Efforts are underway to manage and prevent contamination. No maximum limits for PFAS in food have been set by food safety regulators [185] (Australian Government, 2024). PFAS are used in various applications and do not break down naturally, with increased levels found near sewage treatment plants, landfills, and firefighting foams. Disposal of PFAS-contaminated waste is permitted only in landfills with specific lining systems [204] (EPA South Australia, n.d.). The EPA anticipates more disposal options to become available as the government and waste management sectors respond to PFAS challenges. The PFAS National Environmental Management Plan provides guidance on contamination management [186] (National Chemicals Working Group of the Heads of EPAs Australia and New Zealand, 2020). The Waste Management and Resource Recovery Association of Australia (WMRR) urges the federal government to ban all types of Persistent Organic Pollutants (PFAS) by 2025, noting that the EU and US have already banned PFAS and criticizing Australia's delay in signing the Stockholm Convention on Persistent Organic Pollutants [205] (Sustainability Matters, n.d.).

Microplastics in the Ocean: The Great Pacific Garbage Patch (GPGP) is the largest offshore plastic accumulation zone globally, located between Hawaii and California. It receives 1.15 to 2.41 million tons of plastic annually from rivers, with over half being less dense than water. The GPGP's plastic mass is around 100,000 tons, with 80% originating from land-based sources and 20% from boats and marine sources. Microplastics near the ocean's surface block sunlight for plankton and algae, which are crucial in the marine food web, and leach harmful contaminants, and chemicals [206] (The Ocean Cleanup).

Regulatory and Remediation Efforts: In Australia, public support has grown for synthetic biology solutions for bioremediation in waterways [188] (Shah and Oluto, 2024). Electrokinetic bioremediation uses microbial survival and enzyme secretion to treat polluted soils. The CRC CARE workshop in 2019 identified research gaps in managing PFAS contamination in Australian soils and groundwater. Phyco-remediation using algae, such as Synechocystis sp., offers a green, sustainable water treatment alternative [207–210] (Hobman, Mankad and Carter, 2022; Hassan et al., 2016; Naidu et al., 2020; Marchetto et al., 2021).

‣**Development of New PFAS Treatment Technologies:** Emerging technologies like electrochemical oxidation, supercritical water oxidation, and mechanochemical treatment are being explored for large-scale PFAS-contaminated waste remediation. CSIRO collaborates with industry partners for bioremediation using microbes, though challenges include biodegradation limits, microorganism persistence, and varying treatment performance [211] (Berg et al., 2021).

‣**Investigation and Monitoring:** The Department of Defense and other government agencies conduct extensive investigations to assess PFAS contamination, particularly at military bases and known sources. Monitoring programs are also in place to track PFAS levels in the environment and populations [212] (Department of Defence, n.d.).

‣**Remediation Projects:** Various projects have been initiated to clean up PFAS-contaminated sites, including soil excavation, groundwater treatment, and using activated carbon and other materials to remove PFAS from water [186] (National Chemicals Working Group of the Heads of EPAs Australia and New Zealand, 2020).

‣**Public Health Actions:** Health advisories and guidelines have been issued to inform and protect communities affected by PFAS contamination. This includes providing alternative water supplies and issuing dietary advice to minimize exposure [185] (Australian Government, 2024).

‣**Litigation:** Australia faces legal actions and class-action lawsuits due to PFAS contamination. Affected communities are seeking compensation for property-value loss, health impacts, and environmental damage, citing inadequate information and mitigation efforts. Some cases have resulted in settlements providing financial compensation [213,214] (Shine Lawyers, n.d.; The Guardian, 2023).

‣**Government Investigations:** The Australian Senate and other agencies are investigating PFAS contamination to assess its extent, effectiveness, and community impact. These investigations aim to identify sources, develop remediation strategies, and improve public health protection [215] (Contact, 2018).

‣**Future Directions:** Research is crucial for understanding PFAS, their environmental behavior, health impacts, and remediation technologies. Australia participates in international initiatives to share knowledge and strategies. Strengthening regulations and monitoring programs is vital for better protecting human health and the environment. [188,216] (Department of Foreign Affairs and Trade, n.d.; Shah and Oluto, 2024).

4.2. VIET NAM Briefing: PFAS Impact and Activities

Viet Nam's transition from a centrally planned to a market economy has elevated the country from one of the lowest in the world to a lower middle-income status. Vietnam is becoming one of the most rapidly developing countries in Southeastern Asia [217] [World Bank.org, 2024]

‣The Vietnamese government is increasingly focused on regulating chemicals, including those that fall under the category of per- and poly-fluoroalkyl substances (PFAS), often referred to as "forever chemicals." Although Vietnam has not yet implemented specific regulations on all PFAS chemicals, it has made considerable progress in managing persistent organic pollutants (POPs), which include some PFAS substances like PFOA (perfluorooctanoic acid) and PFOS (perfluoro octane sulfonate). These efforts are aligned with Vietnam's obligations under the Stockholm Convention, to which the country has been a party since 2004 [218] (United Nations Development Programme, 2016). The use of PFOS, for example, has been restricted since 2010, and the government continues to work on monitoring PFAS pollution, particularly in water and seafood [219,220] (Enviliance Asia, 2022; PanNature, 2019).

Vietnam's Ministry of Natural Resources and Environment (MONRE) and the Ministry of Industry and Trade (MOIT) have also been urged to strengthen PFAS monitoring and conduct further research on their environmental and health impacts. Future regulations are expected to evolve based on these studies and the global trend toward phasing out PFAS usage in specific products like firefighting foams [219–221] (Enviliance Asia, 2024; PanNature, 2024; Vietnam National Assembly, 2017).

Vietnam is in the initial stages of developing specific guidelines for handling and disposing of PFAS chemicals. Current guidelines for chemical management, including hazardous chemicals like PFAS, fall under the Law on Chemicals and the Environmental Protection Law. Under this framework, the Ministry of Natural Resources and Environment (MONRE) and other regulatory bodies are tasked with issuing guidelines for safely handling and disposing of persistent organic pollutants (POPs), including some PFAS compounds like PFOA and PFOS.

‣Key areas of focus include:

1. Monitoring and Inventory: The government is working towards compiling an inventory of PFAS chemicals, particularly in firefighting foams and industrial applications. This is seen as a necessary step for understanding where PFAS are used and where the highest pollution risks exist.

2. Waste Management Regulations: While Vietnam has robust waste management guidelines, specific PFAS-related disposal methods are still evolving. The general approach involves preventing environmental releases by regulating waste treatment facilities. Hazardous waste, such as PFAS-contaminated materials, must be treated in controlled environments to avoid environmental contamination.

3. Stockholm Convention Compliance: As a signatory to the Stockholm Convention, Vietnam must follow international guidelines for the disposal of PFOS and other similar chemicals. This involves eliminating or reducing the use of these chemicals in products and ensuring proper destruction methods for waste containing these substances [218,221,222] (United Nations

Development Programme, 2016; Vietnam National Assembly, 2017; World Health Organization, 2009).

‣While Vietnam's PFAS handling and disposal guidelines are still developing, ongoing legislative amendments and international cooperation are expected to guide future regulatory measures. Public awareness about PFAS in Vietnam remains relatively low compared to regions like the US and Europe, where PFAS issues are more widely reported and discussed. In Vietnam, information on PFAS is not as accessible, and most of the population is unfamiliar with these chemicals' risks to health and the environment [220] (PanNature, 2019).

However, there have been efforts to raise awareness, mainly through reports and campaigns from environmental organizations, which have worked on surveys and research in collaboration with international organizations like IPEN (International Pollutants Elimination Network) [223]. Despite the lack of widespread public awareness, the Vietnamese government has acknowledged the presence of PFAS contamination, particularly in water and seafood. Media coverage and environmental studies have highlighted pollution, but these issues are not yet part of the country's mainstream public discourse [220] (PanNature, 2019).

‣Moving forward, increased governmental action on PFAS regulation and monitoring, as well as collaborations with international bodies, could potentially help raise public consciousness about the dangers of PFAS. Currently, Vietnam does not have widespread initiatives specifically aimed at developing innovative solutions for PFAS bioremediation. However, the country has shown interest in broader environmental and pollution control technologies, particularly in the context of its obligations under international agreements like the Stockholm Convention. There is ongoing collaboration with international organizations and experts in dealing with persistent organic pollutants (POPs), including PFAS [220] (PanNature, 2019).

Given the growing recognition of PFAS contamination, Vietnam will likely look to global advancements in bioremediation techniques and may eventually adopt or collaborate on such solutions. Vietnam's environmental strategy currently focuses more on monitoring, regulating, and preventing the further spread of PFAS in water, industrial sites, and food products [220] (PanNature, 2019).

‣Most innovative efforts in bioremediation for PFAS are happening in regions with advanced research ecosystems, such as the US, Europe, and Australia. These initiatives include the development of technologies that use microbes or engineered enzymes to break down PFAS compounds, which could be crucial for addressing water and soil contamination in countries like Vietnam in the future [224] (Dai et al., 2022).

‣**Testing for PFAS Contamination in Drinking Water:** Testing for PFAS contamination in drinking water in Vietnam is not yet part of a widespread or systematic government initiative. PFAS monitoring is still limited, and testing is generally not conducted as part of routine water quality assessments for the public. However, specific studies and reports, especially by environmental organizations, indicate PFAS contamination in water sources, particularly near industrial areas [220] (PanNature, 2019).

‣Recommendations have been made to the government to strengthen PFAS testing, especially in groundwater and areas near suspected hot spots such as industrial zones and locations using firefighting foams. These recommendations include joint monitoring efforts by the Ministry of Natural Resources and Environment (MONRE) and the Ministry of Industry and Trade (MOIT) [220] (PanNature, 2019).

‣**Regulation and Monitoring of PFAS in Food Products:** The Vietnamese government has made strides in regulating persistent organic pollutants (POPs) like PFOS and PFOA under international conventions such as the Stockholm Convention. However, PFAS monitoring and regulations remain limited, particularly for drinking water. Vietnam has not yet established Maximum Residue Limits (MRLs) specifically for PFAS in food products. The regulatory framework for managing chemicals in Vietnam, including PFAS, is still evolving [220] (PanNature, 2019).

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‣**Impact on Marine Ecosystems:** PFAS chemicals are highly persistent and do not break down easily in the environment, leading to their accumulation in water, sediments, and living organisms. Research has shown that PFAS exposure can negatively affect marine ecosystems:

1. Bioaccumulation: PFAS compounds can accumulate in the tissues of marine organisms, especially those higher up the food chain, such as fish and marine mammals. Over time, the concentration of these chemicals increases, posing harm to predators, including humans, who consume contaminated seafood [225] (USEPA, 2016).

2. Toxicity to Marine Species: Studies have demonstrated that PFAS can affect marine life's reproduction, growth, and immune functions. For instance, exposure to PFOS and PFOA (common PFAS compounds) has been linked to developmental problems, liver toxicity, and endocrine disruption in fish and amphibians [226] (Zhao et al., 2011).

3. Impact on Aquatic Food Chains: PFAS in water bodies can disrupt aquatic ecosystems by affecting the health and survival of species at various levels of the food web. This contamination impacts not only fish but also other marine organisms like crustaceans, mollusks, and seabirds that rely on these food sources [227] (Xie et al., 2019).

‣Given their persistence and bioaccumulate nature, PFAS poses a significant long-term risk to marine ecosystems. International studies and environmental monitoring programs increasingly recognize the need for better management and remediation strategies to mitigate the harmful effects of PFAS on marine life [227] (Xie et al., 2019).

‣Future Directions: As awareness of PFAS risks increases, there may be future developments in setting safety thresholds for food products, particularly as Vietnam aligns more closely with international standards and regulations concerning chemical contaminants in food [220] (PanNature, 2019).

‣PFAS in Food Packaging and Pesticides: Vietnam has not enacted specific bans or restrictions on using PFAS in food packaging. The country has begun regulating certain chemicals, like PFOS and PFOA, under its obligations to international conventions. The focus has been mainly on industrial applications and environmental pollution rather than food packaging [220] (PanNature, 2019).

‣While the use of PFAS in pesticides has been a growing concern in some other countries, limited information is available on their use or regulation in Vietnam's agricultural practices. Vietnam's chemical management framework is evolving, and while certain hazardous chemicals used in industrial processes are monitored, PFAS in pesticides has not been explicitly addressed in the country's legislation. However, given global trends and increasing awareness of the environmental and health impacts of PFAS, Vietnam may follow international examples in restricting these substances in agricultural applications, including pesticides, in the future [220] (PanNature, 2019).

‣Vietnam actively participates in numerous international collaborations and efforts focused on researching and managing PFAS contamination. These partnerships enhance Vietnam's capability to address PFAS challenges by sharing information and resources and working together. Here are some major international collaborations and efforts involving Vietnam:

1. Stockholm Convention on Persistent Organic Pollutants: Vietnam is a party to the Stockholm Convention, an international treaty aimed at eliminating or restricting the production and use of persistent organic pollutants (POPs), including specific PFAS compounds like PFOS and PFOA. Under this convention, Vietnam is committed to:

o Phasing Out Production and Use: Gradually eliminating the manufacture and use of listed PFAS substances [228] (UNEP, 2019).

o Monitoring and Reporting: Regularly monitoring POPs in the environment and reporting findings to the Convention's Secretariat [228][(UNEP, 2019).

o Capacity Building: Enhancing national capabilities to manage and reduce POPs through training and technical assistance [228] (UNEP, 2019).

2. Collaboration with International Environmental Organizations Vietnam collaborates with various international environmental NGOs and networks to address PFAS contamination:

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o International Pollutants Elimination Network (IPEN): Vietnam works with IPEN to conduct surveys, research, and advocacy to eliminate toxic pollutants, including PFAS. This partnership supports Vietnam in developing strategies for PFAS management and remediation [223] (IPEN, 2020).

o PanNature: As part of its membership in IPEN, PanNature engages in projects that monitor PFAS pollution and promote sustainable practices to reduce contamination [220] (PanNature, 2019).

3. Regional Cooperation within ASEAN Vietnam participates in ASEAN (Association of Southeast Asian Nations) environmental initiatives focused on chemical management and pollution control:

o ASEAN POPs Protocol: This regional agreement complements the Stockholm Convention by addressing POPs within Southeast Asia. Vietnam collaborates with neighboring countries to harmonize regulations, share best practices, and implement joint projects targeting PFAS reduction [229] (ASEAN, 2018).

o Regional Workshops and Training Programs: Vietnam participates in regional capacity-building efforts, including training on PFAS detection, management, and remediation procedures [229] (ASEAN, 2018).

4. Research and Development Partnerships Vietnamese academic and research institutions partner with international universities and research centers to advance PFAS-related studies:

o Joint Research Projects: Collaborative research initiatives focus on understanding the environmental and health impacts of PFAS, developing innovative remediation technologies, and assessing the effectiveness of regulatory measures [224] (Dai et al., 2022).

o Knowledge Exchange Programs: These programs facilitate the exchange of expertise and technical knowledge between Vietnamese scientists and their international counterparts, fostering innovation in PFAS management [224] (Dai et al., 2022).

5. Technical Assistance and Funding from International Bodies: Vietnam receives support from global organizations to enhance its PFAS management capabilities:

o United Nations Environment Program (UNEP): UNEP provides technical assistance, funding, and guidance to help Vietnam implement PFAS regulations, conduct environmental assessments, and develop remediation strategies [228] (UNEP, 2019).

o World Bank and Other Funding Agencies: These organizations may fund projects to reduce PFAS pollution, improve waste management systems, and upgrade industrial processes to minimize PFAS emissions [230] (World Bank, 2020).

6. Participation in Global Forums and Conferences: Vietnamese representatives actively participate in international conferences and forums focused on chemical safety and pollution control:

o Global Chemical Safety Forums: These events provide platforms for Vietnamese policymakers and scientists to share experiences, learn about global advancements in PFAS management, and collaborate on international initiatives [228] (UNEP, 2019).

o Workshops and Seminars: Participation in specialized workshops helps Vietnam stay updated on the latest research, technologies, and regulatory trends related to PFAS [228] (UNEP, 2019).

7. Adoption of International Best Practices: Through these collaborations, Vietnam adopts international best practices in PFAS management:

o Incorporating Global Norms and Guidelines: Integrating global norms and guidelines into national legislation to regulate PFAS use and emissions effectively [228] (UNEP, 2019).

o Public Awareness Campaigns: Leveraging international expertise to design and implement campaigns that educate the public and industries about the risks of PFAS and the importance of responsible chemical management [223] (IPEN, 2020).

‣**Future Directions:** Vietnam continues to expand its international collaborations to address PFAS challenges better. Future efforts may include:

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• Expanding Monitoring Networks: Establishing more comprehensive PFAS monitoring systems with international partners [228] (UNEP, 2019).

• Innovative Remediation Technologies: Investing in innovative technologies developed through international research partnerships to remediate PFAS-contaminated sites effectively [224] (Dai et al., 2022).

• Policy Development Support: Receiving ongoing support to develop and enforce robust PFAS regulations aligned with global standards [230] (World Bank, 2020).

‣**Conclusion:** Vietnam's participation in international collaborations is crucial for advancing its PFAS research and management efforts. By leveraging global expertise, resources, and coordinated strategies, Vietnam is enhancing its ability to mitigate the environmental and health impacts of PFAS contamination. These partnerships support national objectives and contribute to global efforts to address persistent organic pollutants.

‣**PFAS Contamination in Landfill Management:** PFAS contamination is increasingly recognized as a significant issue in landfill management globally, and Vietnam is no exception. PFAS compounds are often found in landfill leachate, the liquid that drains through landfills and can carry these toxic chemicals into groundwater and surrounding ecosystems [225] (USEPA, 2016). Landfills can become a significant source of PFAS contamination because many consumer products containing PFAS—such as food packaging, textiles, and non-stick products—end up in landfills. As these products break down, PFAS can leach out into the environment [224] (Dai et al., 2022).

Effective landfill management strategies for PFAS include containment, treatment of leachate, and limiting the types of PFAS-containing products that enter landfills. In the future, Vietnam is likely to focus more on this issue as the country continues to align its environmental policies with international standards, as awareness of PFAS contamination grows, and when it becomes beneficial to do so [224] (Dai et al., 2022).

‣**Impact of PFAS on Agriculture:** In Vietnam, where agriculture is a vital part of the economy, the presence of PFAS in water sources or soils near industrial zones or landfills could pose a risk to crop safety [225] (USEPA, 2016). Since PFAS are resistant to degradation, they can remain in agricultural environments for extended periods, impacting the quality and safety of food products [226] (Zhao et al., 2011). Although there is not yet widespread regulation or testing for PFAS in agricultural settings in Vietnam, international concern and emerging research suggest that this issue will require more attention in the future [227] (Xie et al., 2019).

4.3. CANADA Briefing: PFAS Impact and Activities

‣Canada regulates PFAS under the Chemicals Management Plan (CMP), which evaluates and manages substances posing risks to health or the environment [231] (Government of Canada, 2023a). Environment and Climate Change Canada (ECCC) guides managing and disposing of PFAS, including regulatory requirements under CEPA [232] (ECCC, 2023). Canadian universities and environmental agencies are involved in research, with support from Natural Resources Canada (NRCan) [233] (University of Toronto, 2024).

‣Municipalities follow Health Canada which sets the guidelines for PFAS in drinking water health [234] (Health Canada, 2024a).

‣Canada has not yet established specific MRLs for PFAS in food products. The public can track the latest developments under the Pesticide Residue Program from the Canadian Institute for Food safety [235] (CIFS, 2021). Canada restricts certain PFAS under the Canadian Environmental Protection Act (CEPA). For example, the Prohibition of Certain Toxic Substances Regulations lists specific PFAS (like perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS)) as prohibited substances, meaning their use in products, including food packaging, is restricted [236] (Government of Canada, 2024a). Under the Pest Control Products Act, the Pest Management Regulatory Agency (PMRA) oversees the regulation of pesticides. PFAS are considered under this framework when evaluating pesticides for registration, and certain PFAS chemicals are restricted from use in agricultural products due to their toxicity and persistence in the environment [237] (Health Canada, 2024b).

‣Canada regulates PFAS discharge into waterways through several legal frameworks, including CEPA and the Fisheries Act. The Pollution Prevention Provisions of the Fisheries Act make it illegal to deposit harmful substances, including PFAS, into water that could affect fish or fish habitat [238] (Government of Canada, 2024c). In addition, the Wastewater Systems Effluent Regulations (WSER) establish national effluent quality standards for pollutants discharged into waterways, including toxic substances like PFAS [239] (ECCC, 2024).

‣Canada actively participates in international efforts such as the Stockholm Convention on Persistent Organic Pollutants (POPs), which seeks to eliminate or restrict the production and use of persistent organic pollutants like PFAS [238] (Government of Canada, 2024c). Canada has committed to phasing out specific PFAS under this convention [240] (Government of Canada, 2024d). Canada also collaborates with the Organization for Economic Co-operation and Development (OECD), particularly within the OECD’s PFAS Working Group, which facilitates international cooperation on PFAS management, research, and data sharing [241] (OECD, 2024).

‣International collaboration has positively impacted Canada’s approach to PFAS. For example, Canada’s commitment to the Global Monitoring Plan under the Stockholm Convention has led to improvements in environmental monitoring and the regulation of PFAS [242] (Government of Canada, 2024b). Additionally, knowledge sharing with the European Union and the United States has influenced Canada’s regulatory policies and risk assessments for PFAS. This international cooperation has led to better scientific understanding and more effective national actions in reducing PFAS exposure (Government of Canada, 2024b).

‣Through several government and academic institutes, Canada is aggressively researching the long-term health effects of per- and polyfluoroalkyl substances (PFAS) exposure. With an emphasis on PFAS’s impacts on human health, particularly its connections to cancer, thyroid disorders, and immune system disruption, Health Canada has carried out many risk evaluations on the chemical [243] (Health Canada, 2023). Studies on PFAS are also funded by the Canadian Institutes of Health Research (CIHR), which also looks at how they affect vulnerable groups like children and pregnant women [244] (CIHR, 2024). Furthermore, because higher amounts of PFAS have been found in wildlife and food sources in Arctic populations, the Northern Contaminants Program (NCP) is looking into the consequences of PFAS there [245] (NCP, 2024).

‣PFAS are increasingly recognized as a critical public health issue in Canada due to their widespread environmental presence, persistence, and potential for adverse health effects [246] (Government of Canada, 2023b). Health concerns are heightened in communities where PFAS contamination has been identified (e.g., near military bases, firefighting training sites, or industrial facilities), and governments are taking steps to mitigate exposure [247] (Military.com, 2019). Efforts include stricter regulations, improved water testing, and public health advisories to reduce PFAS risks [240] (Government of Canada, 2024d).

4.4. EUROPE: PFAS Impact and Activities

PFAS in Food and Drinking Water: PFAS has been detected in food and drinking water across Europe [92] (EPA, 2024d). A study found over 99% of bottled water samples from 15 countries contained PFAS [248] (University of Birmingham, 2024). These chemicals are persistent in the environment and can accumulate in the bodies of living organisms [25] (EPA, 2024).

‣**Bans and Regulations:** The European Chemicals Agency (ECHA) proposed a ban on approximately 10,000 PFAS in February 2023 [249] (ECHA, 2023). This proposal aims to restrict the production, use, and sale of PFAS in consumer products [249] (ECHA, 2023). The ban is part of the EU's REACH regulation, which seeks to protect human health and the environment from hazardous chemicals [249] ECHA, 2023).

‣**Public Awareness Campaigns:** Public awareness campaigns, such as the Forever Pollution Project, have highlighted the widespread contamination of PFAS across Europe [250] (Forever Pollution Project, 2023). These campaigns aim to inform the public about the risks associated with PFAS and encourage regulatory action [250] (Forever Pollution Project, 2023).

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•**Remediation Innovations and Efforts:** Several innovative projects are underway to address PFAS contamination in Europe [251] (EC, 2024). These projects focus on PFAS detection, distribution, treatment, and holistic strategies to reduce their environmental impact (EC, 2024). Techniques such as bioremediation, chemical oxidation, and advanced oxidation processes are being explored [252] (Das et al., 2024).

‣**Monitoring Drinking Water PFAS Levels:** Monitoring PFAS levels in drinking water is crucial for assessing exposure and health risks [25] (EPA, 2024). The European Environment Agency (EEA) has highlighted the need for systematic mapping and monitoring of potentially polluted sites [253] (EEA, 2023). National monitoring activities have detected PFAS in the environment across Europe [253] (EEA, 2023).

‣**MCL Threshold:** The Maximum Contaminant Level (MCL) for PFAS in drinking water varies across Europe. The European Union has set guidelines to limit PFAS concentrations in drinking water to protect public health [249] (ECHA, 2023).

‣**Lawsuits:** Several lawsuits have been filed in Europe concerning PFAS contamination. These lawsuits often involve claims of environmental damage and health impacts due to PFAS exposure [249] (ECHA, 2023).

‣**Guidelines and Recommendations:** The ECHA and other regulatory bodies have issued guidelines and recommendations for managing PFAS contamination. These guidelines aim to reduce PFAS use, improve monitoring, and promote remediation efforts [249] (ECHA, 2023).

‣**Human Health Effects:** PFAS exposure has been linked to a range of health issues, including increased cholesterol levels, changes in liver enzymes, thyroid disease, decreased vaccine response in children, and increased risk of kidney and testicular cancers [25] (EPA, 2024). The toll on human health is significant, with teenagers in Europe facing health risks from exposure to PFAS [253] (EEA, 2023).

‣**Cost of PFAS Remediation:** The cost of PFAS remediation in Europe is substantial. Estimates suggest that the societal costs due to harm to human health and remediation efforts are tens of billions of EUR annually [249] (ECHA, 2023). Professor Hans Peter Arp estimates the cleaning costs to be €238 billion in the EU alone, with global costs extrapolated to €16 trillion per year [254] (ChemSec, 2023).

‣**Mismanagement of Landfills:** The mismanagement of landfills in Europe has led to significant environmental and public health concerns Unauthorized landfill sites can generate emissions, unpleasant odors, and contaminate nearby soil and watercourses [255] (European Parliament, 2020). Proper management and regulation are essential to mitigate these risks.

‣**Plastic Recycling Issues:** Plastic recycling in Europe faces several challenges. Only about 30% of plastic waste is collected for recycling, while 43% is incinerated, and 25% is still landfilled. A substantial proportion of plastics ends up in the sea, posing environmental threats [180,256–260] (PWC, 2019; EFSA, 2024; Plastics Europe, 2019; The World Economic Forum, 2016; EC, 2024; Geyer et al, 2017). Improving recycling infrastructure and reducing waste export are crucial steps toward addressing these issues [261] (EU Science Hub, 2024)

‣**Food Contact Packaging:** Food contact packaging in Europe is regulated to ensure safety. However, mismanagement and non-compliance with regulations can lead to PFAS contamination Ensuring that all food contact materials comply with EU regulations is essential to protect public health and food quality [262] (EC Europa, 2024)

‣**PFAS Impact on the SDGs of 2030:** The widespread contamination of PFAS poses a significant challenge to achieving the Sustainable Development Goals (SDGs) of 2030. Efforts to remediate PFAS and reduce their use are crucial for protecting human health and the environment. The forecast for PFAS remediation globally involves significant investment and regulatory action to mitigate their impact [263] (Bluefield Research, 2022).

‣**Conclusion:** PFAS contamination is a significant environmental and public health issue in Europe. Efforts to ban, regulate, and remediate PFAS are ongoing, with public awareness campaigns playing a crucial role in driving regulatory action. Continued research and monitoring are essential to mitigate the impact of PFAS on human health and the environment.

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4.5. UNITED STATES OF AMERICA: PFAS Impact and Activities

Per- and polyfluoroalkyl substances (PFAS) have emerged as a significant environmental and public health concern in the United States. These "forever chemicals" are known for their persistence in the environment and potential to cause adverse health effects. The federal and state governments have been actively working to address PFAS contamination through various legislative and regulatory measures [92,264] (EPA, 2024d; Source Intelligence, 2024).

‣**Impact of PFAS:** PFAS have been detected in water supplies, soil, and food products nationwide, leading to widespread exposure. Studies have linked PFAS exposure to various health issues, including cancer, liver damage, and immune system effects [265] (NIEHS, 2022). The Environmental Protection Agency (EPA) has established the first-ever national drinking water standard for PFAS to protect communities from these harmful chemicals [148] (EPA, 2024a).

‣**Legislation Activities:** The Biden-Harris administration has taken several bold actions to tackle the PFAS crisis. In April 2024, the EPA designated two widely used PFAS—PFOA and PFOS—as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund. This designation aims to improve transparency and accountability in cleaning up PFAS contamination [162,266] (EPA, 2024f; Congress.gov 2021). Additionally, the EPA has issued a national drinking water standard and provided funding to help states and territories implement PFAS testing and treatment [148] (EPA, 2024a).

‣**Effective PFAS Bioremediation Methods:** Recent advancements in PFAS bioremediation have shown promise for scalable solutions. One innovative approach involves using plant-based materials combined with microbial fungi to adsorb and degrade PFAS. This method, known as Renewable Artificial Plant for In-Situ Microbial Environmental Remediation (RAPIMER), utilizes corn stover to create a porous framework that supports fungal growth and PFAS degradation [265] (NIEHS, 2022)

‣**PFAS Remediation Capacity-Building Programs and Crisis Guidance:** To address PFAS contamination in the food industry and agriculture sectors, several capacity-building programs have been initiated [267] (Lee et al, 2024). The USDA has developed a roadmap to tackle PFAS on farmland, focusing on detecting contamination, developing tools to prevent harm, and promoting scientific exchange among farmers, scientists, and stakeholders. These programs aim to reduce PFAS risks in food crop production and enhance sustainable farming practices [268] (USDA, 2024). Numerous public awareness guidance campaigns are promoted such as the NRDC October 2024 Fact Sheet, "Toxic Drinking Water: Addressing the PFAS Contamination Crisis. [269] (NRDC, 2024).

‣**Landfills:** PFAS contamination in landfills is a significant environmental concern. PFAS-containing products, such as clothing, carpet, bedding, and food packaging, can release PFAS into landfill leachate, contaminating soil and groundwater. Some landfills divert leachate for treatment at wastewater treatment plants, but the challenge remains to effectively manage and mitigate PFAS contamination [270,271] (Environmental Health News, 2024; ACS 2024).

‣ **Chemical Waste in Waterways and Groundwater:** PFAS contamination in waterways is a critical issue. PFAS can enter waterways through various pathways, including industrial discharges, landfill leachate, and runoff from contaminated agricultural lands. The EPA has been awarded research grants to study the impact of PFAS on waterways and develop strategies to reduce contamination. Efforts are underway to improve water treatment technologies and prevent PFAS from entering water sources [272–276] (EPA, 2024g; Craig et al, 2024; Jensen, 2024; COSRI, 2024; Phys.org., 2024).

‣**Conclusion:** The efforts to address PFAS contamination in the USA reflect a growing recognition of the need for stringent regulations, implementation of HACCP-based food safety systems [277] (Lee et al., 2021), and proactive measures to protect public health and the environment. By implementing comprehensive legislation and regulatory actions, the government aims to mitigate the impact of PFAS and ensure safer living conditions for all Americans [278] (Governing, 2024).

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5. Discussion

5.1. Crisis Multi-Faceted Issue, Exacerbated by Mismanagement

In analyzing "The PFAS Crisis and Colossal Catastrophic Systems Failure" issue using the Domino Effect Model, Swiss Cheese Model, and Ishikawa Fishbone Diagram we can identify how multiple failures and gaps in various systems have led to the widespread contamination and health impacts associated with PFAS compounds [279–281] (Heinrich,1931, Shabani et al 2023, Ishikawa, 1990).

●Systems Accident Analysis

Systems accident analysis involves examining accidents within the context of the entire system, rather than focusing solely on individual components or human error [282] (Leveson, 2011).

●This approach considers the interactions between technical, human, organizational, and environmental factors [282] (Leveson, 2011).

●Models like Domino Effect, Swiss Cheese Theory, and Ishikawa Fishbone Root Cause Analysis are used to identify systemic issues and improve safety [279,283,284] (Reason, 1990; Heinrich, 1931; Ishikawa, 1968).

● Domino Effect Model

The domino effect model, developed by Herbert W. Heinrich, represents an accident sequence as a causal chain of events, similar to a row of dominos that topple in a chain reaction. The fall of the first domino leads to the fall of the second, followed by the third, and so on. This model emphasizes that a single cause is never sufficient to explain why an incident or injury took place. Instead, it highlights the importance of addressing multiple factors to prevent accidents [279] (Heinrich, 1931).

●Swiss Cheese Theory

The Swiss cheese model, developed by James Reason, illustrates how failures typically result from a combination of factors rather than a single root cause. It likens human systems to multiple slices of Swiss cheese, each with its own holes representing weaknesses. When these holes align, a hazard passes through all layers, leading to a failure. This model emphasizes the importance of having multiple layers of defense to prevent accidents [283] (Reason, 1990).

● Fishbone Root Cause Analysis

Also known as the Ishikawa Diagram, the fishbone root cause analysis is a visual tool used to identify the root causes of a problem. The main problem is placed at the "head" of the fish, and potential causes are categorized into branches, such as Methods, Machines, People, Materials, Measurements, and Environment. This method helps teams systematically explore and address the underlying issues [281] (Ishikawa, 1990).

● Problem-Solving Techniques

Effective Problem-solving is an organized strategy to find, evaluate, and address challenges. Common techniques include:

1. Define the Problem: Clearly state the issue.
2. Brainstorm Solutions: Create a list of probable solutions.
3. Evaluate Solutions: Evaluate the feasibility and impact of each solution.
4. Implement the Solution: Put the selected solution into effect.
5. Monitor and Review: Evaluate the solution's efficacy and make any necessary adjustments. [285] (Anderson & Fagerhaug, 2006).

Combining systems accident analysis, fishbone root cause analysis, the domino effect model, and the Swiss cheese theory can significantly enhance an organization's ability to detect and successfully resolve issues.

By understanding the systemic nature of accidents, identifying root causes, and applying structured problem-solving methods, organizations can improve safety, efficiency, and overall performance.

5.1.1. Domino Effect Model of Accident Causation

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The Domino Effect Model suggests that a series of interconnected events or failures can lead to a larger catastrophic outcome. In the case of the PFAS crisis, the use of these chemicals in a wide range of products, combined with inadequate regulation and oversight, has created a chain reaction of contamination and health risks. The release of PFAS compounds into the environment has led to their accumulation in water sources, soil, and food supplies, resulting in widespread exposure and long-term health effects for humans and wildlife [286,287] (Grandjean, 2007; Post, 2010).

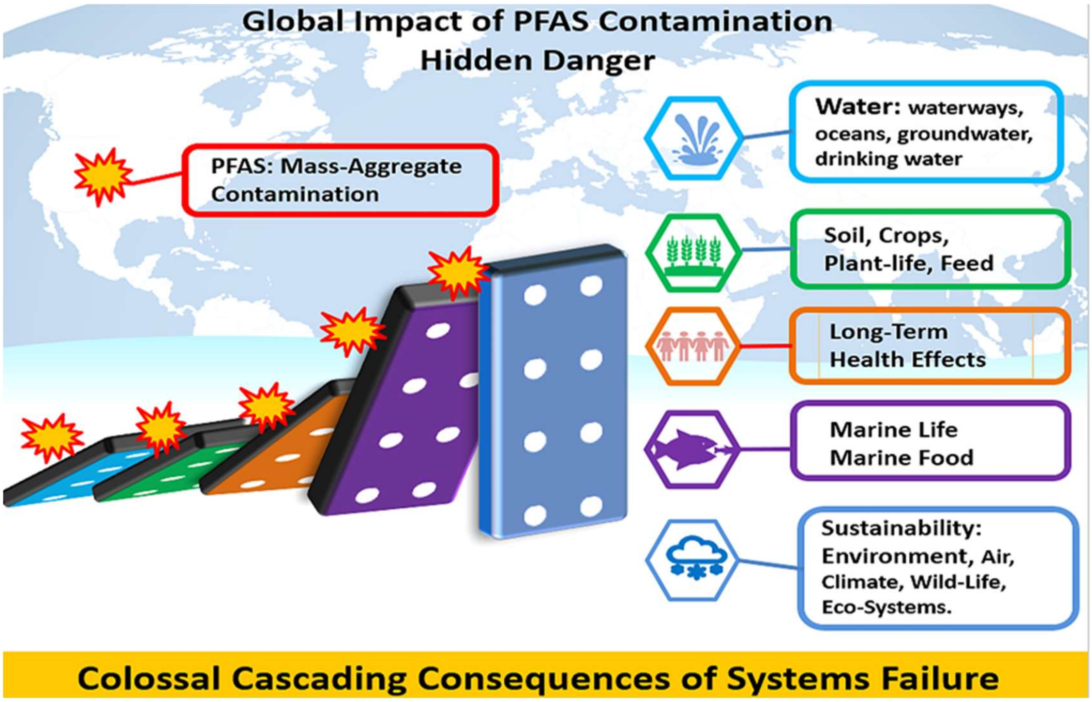

Figure 3. Domino Effect Model of Accident Causation**.**

5.1.2. Swiss Cheese Model

The Swiss Cheese Model demonstrates how numerous layers of security or safeguards can have holes that, when aligned, allow an accident to occur. In the context of the PFAS crisis, regulatory failures, industry practices, and public awareness gaps have all contributed to the persistence of PFAS contamination. The lack of comprehensive regulations, ethical considerations by chemical companies, and potential cover-ups have allowed the problem to escalate and impact communities worldwide [280] (Shabani et al 2023). As illustrated in Figure 4.

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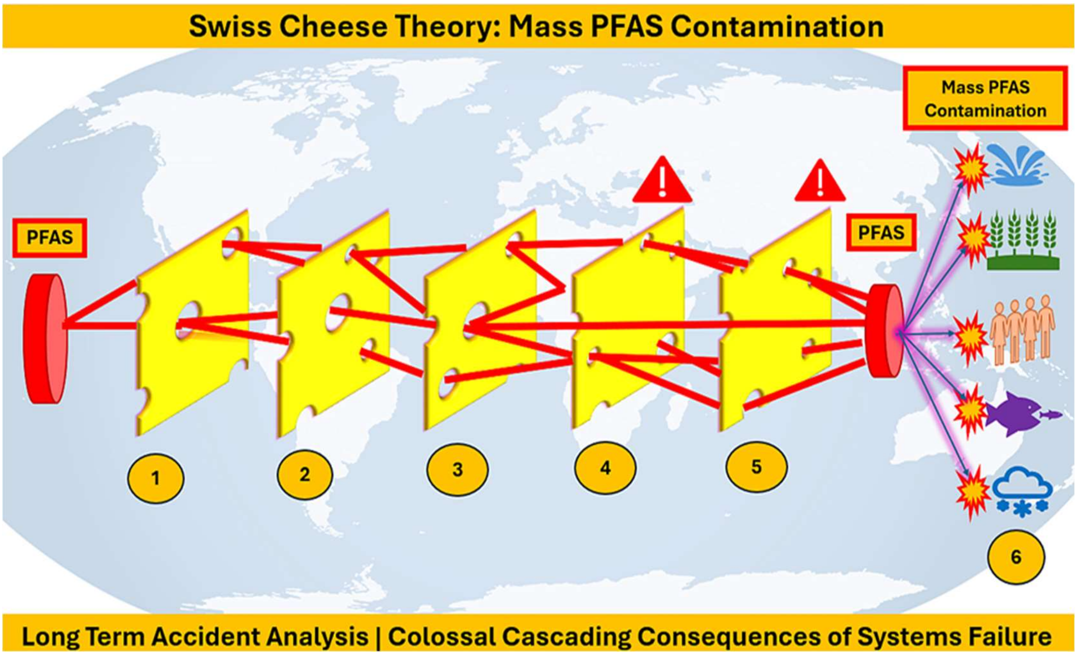

Figure 4. Long-Term Accident Analysis-Colossal Cascading Consequences of Systems Failure Swiss Cheese Model.

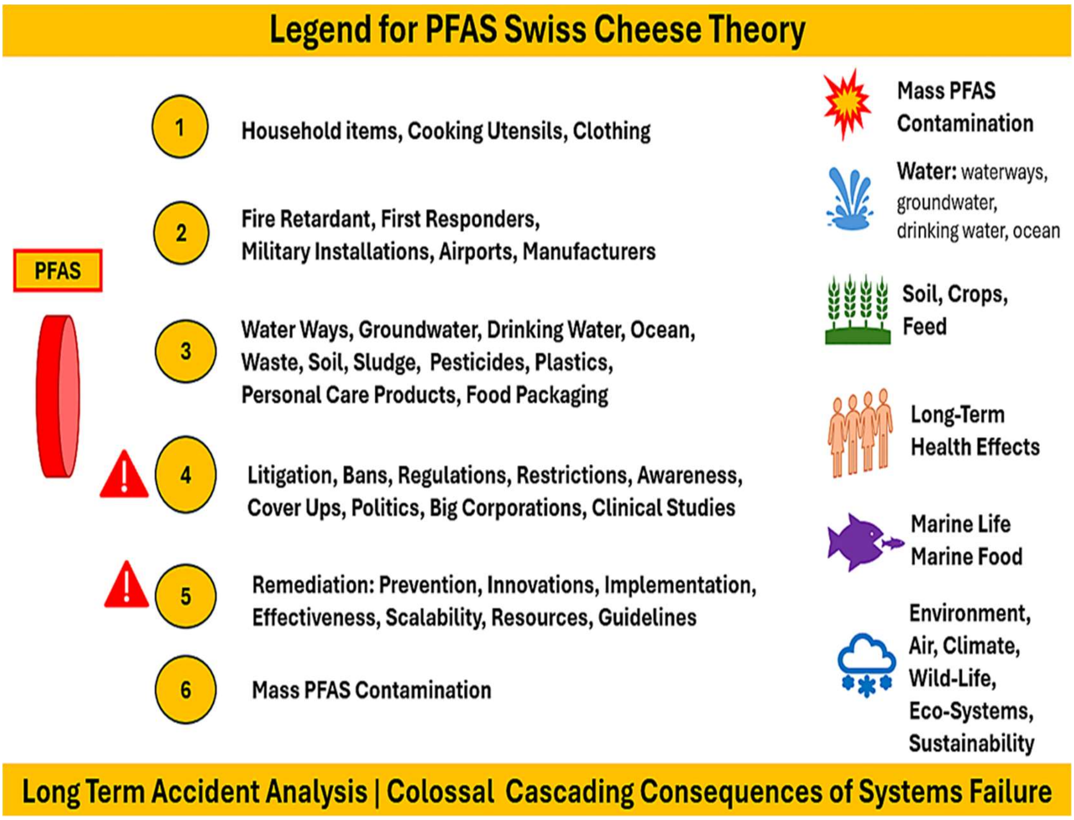

Figure 5. Legend for PFAS Swiss Cheese Theory Systems Failure.

In addressing the PFAS crisis, potential bio-remediation remedies, such as using microorganisms to break down PFAS compounds, offer a promising solution to mitigate contamination and reduce long-term health risks. However, further research and regulatory actions are needed to ensure the effectiveness and safety of these remediation methods.

By applying the Domino Effect Model and Swiss Cheese Model to the PFAS crisis, we can have a deeper understanding of the complex interplay of factors that have contributed to this colossal

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system failure and work towards implementing comprehensive solutions to safeguard public health and the environment.

5.1.3. Ishikawa Fish Bone Root Cause Analyses

The Ishikawa Fishbone Root Cause Analysis is a tool that visually maps probable contributing components to discover the root cause of an issue. In the context of the Global Forever Chemical PFAS Crisis, this method can be particularly useful for understanding the complex factors that have led to widespread PFAS contamination [288] (Ishikawa, 1982).

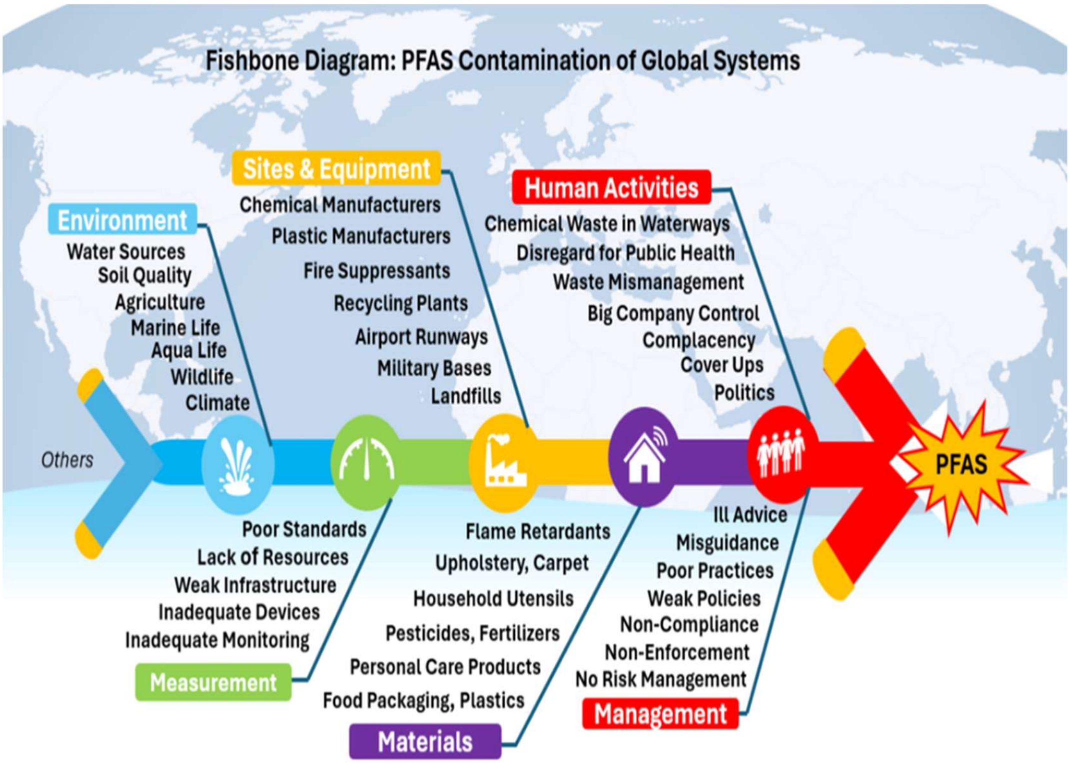

Figure 6. Fish Bone Diagram [281] (Ishikawa,1990).

By systematically breaking down the problem and identifying contributing factors, the Ishikawa Fishbone Root Cause Analysis helps stakeholders develop targeted and effective solutions to address the PFAS crisis [281] (Ishikawa,1990).

‣Identify the Problem: The central issue is the presence of PFAS (per- and polyfluoroalkyl substances) in the environment, particularly in water sources [289] (U.S. Environmental Protection Agency, 2021).

‣The Fishbone Diagram: The horizontal line (the "spine") represents the problem, PFAS Contamination. Branching off this line are major categories of potential causes, "Human Activities”, "Management", "Sites and Equipment", "Materials”, “Environment”, and "Measurement” [290] (Tague, 2005).

•Brainstorm Causes: For each category, brainstorm possible causes of PFAS contamination.

•Materials: Types of PFAS used in products [291] (Buck et al., 2011).

•Sites and Machines (Methods): Industrial processes that release PFAS [64] (Cousins et al., 2020), and

•Equipment that may contribute to PFAS release [292] (Lindstrom et al., 2011).

•Measurement: Inadequate monitoring of PFAS levels [289] (U.S. Environmental Protection Agency, 2021).

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•People: Human activities contributing to PFAS spread [293](Lau et al., 2007).

•Environment: Natural factors affecting PFAS distribution [294] (Newton et al., 2020).

•Management: Policies and practices that may have allowed PFAS use [292] (Lindstrom et al., 2011).

•Waste Mismanagement: Improper disposal and management of PFAS-containing waste [269] (NRDC, 2024).

‣Analyze and Prioritize: Evaluate the potential causes to determine which are most likely contributing to the problem. Prioritize these causes based on their impact and the feasibility of addressing them [290] (Tague, 2005).

‣Develop Solutions: Based on the analysis, develop strategies to mitigate or eliminate the root causes of PFAS contamination. Here are some suggested solutions:

•Materials: Develop and promote the use of safer alternative substances to replace PFAS in products [64] (Cousins et al., 2020).

•Methods: Implement stricter regulations and best practices for industries to reduce PFAS emissions during manufacturing processes [289] (U.S. Environmental Protection Agency, 2021).

•Sites and Machines: Upgrade industrial equipment to prevent PFAS leakage and enhance the efficiency of PFAS capture technologies [294] (Newton et al., 2020).

•Measurement: Establish comprehensive monitoring programs to regularly assess PFAS levels in the environment and identify contamination hotspots [293] (Lau et al., 2007).

•People: Increase public awareness and education on the sources and impacts of PFAS, encouraging responsible consumer behavior [291] (Buck et al., 2011).

•Environment: Implement remediation and cleanup efforts in contaminated areas, using advanced techniques like adsorption and filtration [64] (Cousins et al., 2020).

•Management: Strengthen policies and international agreements to phase out the manufacturing and use of PFAS internationally [292] (Lindstrom et al., 2011).

•Waste Mismanagement: Improve waste management practices to ensure proper disposal and treatment of PFAS-containing waste, reducing environmental contamination [269] (NRDC, 2024).

‣Cost and Impact on SDGs 2030: Bioremediation, a cost-effective and eco-friendly method, can significantly contribute to meeting the Sustainable Development Goals (SDGs) by 2030. The cost of bioremediation varies, but it is generally lower than traditional remediation methods, with estimates ranging from USD 50.7 to USD 310.4 per m^3 of contaminated soil [295] (MDPI, 2024). Implementing bioremediation can help achieve SDGs related to clean water and sanitation (Goal 6), sustainable cities and communities (Goal 11), and life below water (Goal 14) by reducing pollution and promoting environmental sustainability [296,297] (Springer, 2024a; Springer, 2024b).

5.2. The PFAS Impact on the Sustainable Development Goals (SDGs) of 2030

Addressing the PFAS crisis aligns with several United Nations Sustainable Development Goals (SDGs), including:

•Goal 3: Good Health and Well-being: Reducing exposure to harmful chemicals improves public health. The Centers for Disease Control and Prevention (CDC) and the Agency for Toxic Substances and Disease Registry (ATSDR) conducted exposure assessments to determine the impact of PFAS on health. [14] (ATSDR, 2024).

•Goal 6: Clean Water and Sanitation: Ensuring safe drinking water by mitigating PFAS contamination. The U.S. Environmental Protection Agency (EPA) has set the first national drinking water guidelines for PFAS to safeguard communities from exposure. [92] (EPA, 2024d).

•Goal 12: Responsible Consumption and Production: Encouraging sustainable practices and behaviors, and reducing chemical pollution (United Nations, 2015). EPA has been investing in projects to address PFAS contamination in water through the Bipartisan Infrastructure Law [149] (EPA, 2024b).

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•Goal 14: Life Below Water: Protecting marine life and ecosystems from PFAS contamination. The Waterkeeper Alliance has been working to monitor and remediate PFAS pollution in global waterways [298] (Waterkeeper Alliance, 2024).

• Goal 15: Life on Land: Reducing PFAS contamination in soil and terrestrial ecosystems to protect biodiversity2. The OECD has hosted forums to address the environmental impact of PFAS [241] (OECD, 2024).

By tackling the PFAS crisis through comprehensive regulation, public awareness, and individual actions, we can mitigate its impact and move towards a healthier, more sustainable future.

Environmental and Health Challenges

PFAS contamination is a global concern, affecting water supplies, soil, and air. These substances have been found in everything from groundwater and drinking water to the food chain, posing significant threats to food security and nutrition. The persistence of PFAS in the environment complicates remediation efforts, as these compounds do not degrade quickly and can spread across huge areas [299] (Grandjean et al, 2015).

Innovative Bioremediation Methods

Researchers are exploring various bioremediation techniques to address PFAS contamination. These include using microbes and plants to absorb and break down PFAS compounds. Phytoremediation, for example, employs plants like birch and willow trees, which have shown potential in absorbing PFAS from the soil. Innovations in this area are critical for reducing PFAS levels in contaminated sites [300] (C8 Science Panel, 2012).

Future Outlook and Sustainability

The future of PFAS management requires a multifaceted approach. This includes stricter regulations, investment in safer chemical alternatives, continuous monitoring and research, and public awareness about PFAS in consumer products. Sustainable manufacturing and waste management practices are necessary to mitigate these chemicals' environmental footprint [289,301] (U.S. Environmental Protection Agency, 2021; Johnson et al, 2022).

Ongoing Research and Regulatory Efforts

PFAS continues to be a substantial public health problem, prompting ongoing research and regulatory efforts. CDC plays a vital function in studying the health effects of PFAS, guiding mitigation and prevention strategies, and supporting regulatory frameworks to protect communities from these persistent pollutants [88] (CDC, 2024). Continued monitoring and community engagement are vital to effective PFAS management [90–92] (EPA, 2024).

6. Conclusions

6.1. PFAS Crisis: A Multi-Faceted Issue Exacerbated by the Mismanagement of Waste

The PFAS crisis is a multifaceted issue that has been exacerbated by the mismanagement of waste, particularly in the context of wastewater treatment, landfills, and plastic production. The presence of PFAS chemicals in wastewater and landfills has caused their release into the environment, damaging water supplies and soil. [148,164] (EPA, 2024a; EHN, 2022). Additionally, the use of PFAS in plastics has further contributed to the spread of these chemicals in the environment, impacting marine life and aquatic ecosystems [149,302] (UNEP, 2020; EPA, 2024b).

6.2. Wastewater and Landfills

Studies have shown that wastewater treatment plants are a significant source of PFAS contamination in water bodies. The persistence of these chemicals in wastewater effluents can lead to their accumulation in rivers, lakes, and oceans, posing risks and hazards to aquatic life and human health. Landfills also play an impactful role in the release of PFAS compounds into the environment, as leachate from landfills can contain high levels of these chemicals, contaminating groundwater and soil [303] (EPA /pfas-wastewater; Hu et al., 2017).

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6.3. PFAS in Plastics

The use of PFAS in the production of plastics, such as food packaging and consumer goods, has led to the widespread distribution of these chemicals in the environment. When these plastic products are discarded or incinerated, PFAS compounds can be released into the air, water, and soil, contributing to pollution and environmental contamination [140] (Schultes et al., 2020; unep.org, 2024).

6.4. Marine Life and Aqua Ecology

The presence of PFAS compounds in water bodies has been shown to have detrimental effects on marine life and aquatic ecosystems. Bioaccumulation of PFAS in fish and other aquatic organisms can lead to health risks for both wildlife and humans who consume contaminated seafood. Additionally, the disruption of aquatic ecosystems due to PFAS contamination can have long-lasting impacts on biodiversity and ecosystem health [66] (Giesy et al., 2004; eea.euroa.eu, 2006).

In conclusion, the mismanagement of waste, including wastewater, landfills, and plastics, has significantly contributed to the PFAS crisis, leading to widespread contamination and environmental harm [25] (EPA, 2024). Addressing these issues requires comprehensive regulatory actions, improved waste management practices, and sustainable alternatives to PFAS-containing products [304]. Collaborative efforts involving government agencies, scientific research institutions, and environmental organizations are essential to mitigate the impacts of PFAS contamination and protect ecosystems and public health [304].

6.5. Consequences of PFAS Remediation in the Environment

At the levels that are now ubiquitous in some environments, PFASs have a deleterious influence on human health (Sunderland et al., 2019). When there is a demonstrated benefit to human health and available, affordable, and effective technology, it makes sense to eliminate PFAS from the environment. A recent cost-benefit study supports the necessity for remediation, particularly for drinking water sources with high concentrations of PFAS when the benefits to human health outweigh any potential drawbacks [304] (U.S. EPA, 2023a).

6.6. Future Outlook and Sustainability

The future outlook for addressing PFAS contamination is centered on sustainability and comprehensive remediation strategies. Research has shown that PFAS compounds have significant health risks, necessitating a proactive approach to minimize exposure and contamination [286] (Grandjean and Clapp, 2015).

Efforts to tackle the PFAS crisis have been bolstered by strategic initiatives, such as the U.S. Environmental Protection Agency's PFAS Strategic Roadmap, which contains commitments of action from 2021 to 2024. This roadmap emphasizes the importance of reducing PFAS emissions, enhancing detection methods, and accelerating the cleanup of contaminated sites [289] (U.S. EPA, 2021).

One promising area of research is the bioremediation potential of plants to mitigate PFAS contamination. Studies have highlighted the ability of certain plant species to absorb and break down PFAS compounds, offering a cost-effective and sustainable solution for environmental remediation [301] (Johnson et al., 2022).

The C8 Science Panel's assessment of the likely relationship between PFOA exposure and human health effects further underscores the need for stringent regulatory measures and ongoing monitoring to protect public health [300] (C8 Science Panel, 2012).

6.7. Summation

"The ever-increasing mass of PFAS in the global environment necessitates a change in the mass balance, either through increased remediation, reduced emissions, or both." This review explores the potential costs (human health, eco-systems, climate, future generations, sustainability, food security,

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etc.) of relying entirely on increased remediation without decreasing PFAS consumption and emissions. The anticipated annual costs of removing PFAS from the environment at the current rate of emission range from 20 to 7,000 trillion USD. Without major reductions in production and emissions, the costs are anticipated to exceed the world GDP of 106 trillion USD, making it unfeasible to manage PFAS pollution through remediation alone [305] (Ling, 2024).

The only method available to address the mass of PFAS steadily accumulating in the environment is to alter the mass balance by either reducing emissions, increasing removal, or accomplishing both. Integrating sustainable practices within food systems is crucial for supporting a healthy planet. Sustainable food systems can help mitigate PFAS contamination by promoting eco-friendly agricultural practices and reducing the use of harmful chemicals. This approach not only addresses current environmental issues but also supports long-term food security and public health [306] (Varzakas and Smaoui, 2024). This review adds to the ongoing discourse on PFAS policy by focusing more heavily on remediation [305] (Ling, 2024).

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Abbreviations

The following abbreviations are used in this manuscript:

perfluorooctanoic acid (PFOA)
perfluorooctanesulfonic acid (PFOS)

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