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# Environmental And Biological Dynamics Of Pfas: Sources, Exposure Routes, And Health Implication - A Complihesive Review

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***Abstract:*** *This review explores the environmental and health impacts of per- and polyfluoroalkyl substances (PFAS), a group of synthetic, persistent chemicals widely used in industrial and consumer products. The study examines PFAS sources, transport mechanisms, physicochemical properties, exposure pathways, and associated health effects on humans, animals, and plants. PFAS are highly resistant to degradation, bio-accumulative, and capable of long-range environmental transport. Human exposure occurs mainly through contaminated water, food, air, and consumer products, contributing to adverse outcomes such as liver toxicity, cancer, reproductive and developmental disorders. The review highlights regulatory frameworks, emerging remediation technologies, and advances in PFAS source apportionment and biodegradation research. It emphasizes the need for stricter regulations, improved analytical methods, and sustainable management strategies to mitigate PFAS contamination and protect public and ecosystem health.*

**Key words -** Per- and polyfluoroalkyl substances; sources; PFAS exposure pathways

## 1.0 Per- and polyfluoroalkyl substances (PFAS)

PFAS is a group of synthetic chemicals characterized by fluorine atoms bonded to carbon atoms that are persistent in the environment and resistant to degradation (Berg *et al.*,2022).

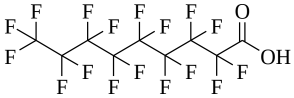
PFAS contamination, a persistent, bioaccumulative, and toxic chemical, is a growing concern in Africa, particularly in Uganda (May *et al.*, 2013). The contamination is primarily caused by industrial development, inadequate waste management practices, and firefighting foams used in airports and military installations. Uganda faces challenges in addressing PFAS exposure due to lack of regulation, limited research, and reliance on untreated surface water (Griffin et al., 2023). The potential bioaccumulation of PFAS in fish and wildlife could affect food safety, particularly in regions reliant on subsistence fishing (Okafor *et al.*, 2023). Despite limited regulation, increasing international pressure and awareness could lead to future policy developments. Uganda's water treatment infrastructure and reliance on untreated surface water pose significant risks to human populations and ecosystems (Nakiyende *et al.*, 2023).

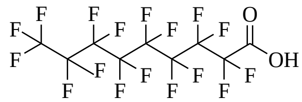
### 1.2 Some examples of Per- and poly-fluoroalkyl substances

PFAS, or per- and poly-fluoroalkyl substances are synthetic compounds that have been extensively utilized in a wide range of consumer and industrial goods (Roth & Petriello, 2022). They are found in a variety of items, including cleaning supplies, water-resistant textiles, nonstick cookware, and firefighting foams. PFAS can find its way into the environment through product use, production procedures, and inappropriate disposal (Pinkard *et al.*,2023). PFAS can build up in the environment and are a persistent material, they have been found in soil, water sources, and wildlife all across the world. Because of the potential harm they could do to human health, PFAS are a cause for concern (Koban & Pfluger, 2023). A few PFAS have been linked to immune system malfunction, developmental disorders, and other health concerns. Concerns about long-term contamination arise from the fact that they are difficult to remove from water sources (Roth & Petriello, 2022).

### 1.3 Examples of the most common priory Perfluoroalkyl Substances and their chemical structures

It's important to note that specific rankings or prioritizations may vary depending on the context and region, here are some of the commonly encountered Perfluoroalkyl Substances compounds. The following are some of the examples of Perfluoroalkyl Substances and their chemical structures.


Perfluorooctanoic acid (PFOA)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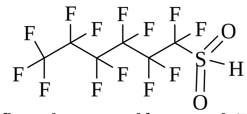
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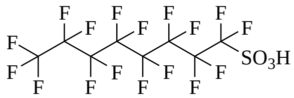
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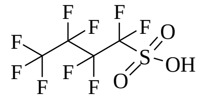
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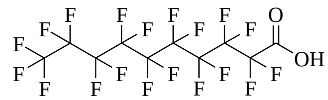
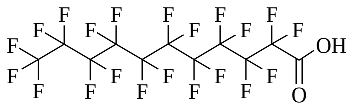

Perfluorodecanoic acid (PFDA)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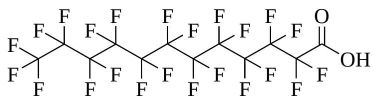
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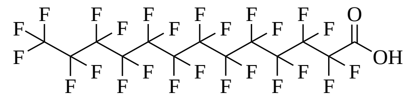
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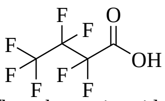
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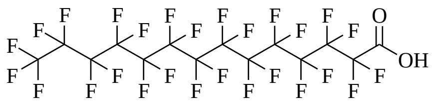
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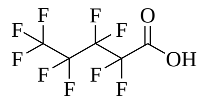
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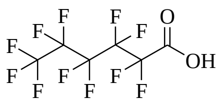
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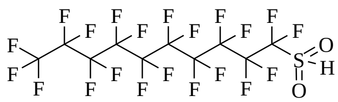
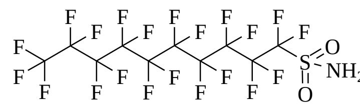
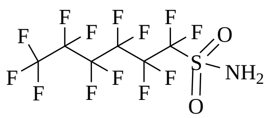
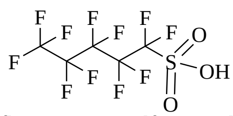
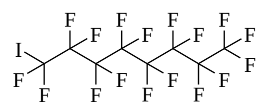
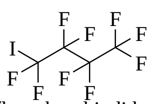

Perfluorodecane sulfonic acid (PFDS)

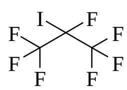

Perfluorodecane sulfonamide (PFDSA)


Perfluorohexane sulfonamide (PFHxSA)


Perfluoropentane sulfonic acid (PFPeS)


Perfluorooctyl iodide (PFOI)


Perfluorobutyl iodide (PFBI)


Perfluorohexyl iodide (PFHxI)

Source; (Caban-Martinez *et al.,*2022; Cousins *et al.,*2020; Mahinroosta & Senevirathna, 2020)

## 2.0 Methodology

This review analyzes literature on the environmental and biological dynamics of per- and polyfluoroalkyl substances (PFAS) sources. It focuses on sources, exposure routes, and health impacts of PFAS. Peer-reviewed articles, government reports, and authoritative databases published between 2011 and 2025 were sourced from databases like PubMed, Scopus, and Web of Science, categorized into environmental sources, human and ecological exposure pathways, and health outcomes. The review identifies patterns, knowledge gaps, and emerging trends in the field.

## 3.0 Sources and Emission Pathways per- and polyfluoroalkyl substances

Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals that pose a significant environmental threat due to their widespread presence and persistence (Sharp *et al.*, 2021). They are used in various industrial processes, including surface coatings, firefighting foams, and chemical production, which can lead to improper disposal, accidental releases, and wastewater discharges (Burkhard & Votava, 2023). Consumer products, such as stain-resistant fabrics, food packaging, non-stick cookware, and waterproof apparel, also use PFAS, which can be released into the environment through wastewater treatment systems and landfill leachate (Zhang *et al.*,2023).

Aqueous Film-Forming foam (AFFF) is used for firefighting, but improper storage, handling, and disposal can result in PFAS release into soil, groundwater, and surface water bodies. Atmospheric deposition contributes to the widespread distribution of PFAS in the environment (Kurwadkar *et al.*,2022). Landfill and waste disposal can also leach PFAS into the surrounding environment, including groundwater and surface water. PFAS present in domestic and industrial wastewater can pass through conventional wastewater treatment processes, leading to their discharge into receiving water bodies (Stoiber et al., 2020). Additionally, PFAS can accumulate in biosolids and be applied to agricultural land, potentially contaminating soil and groundwater (Ogbuewu & Nnaji, 2023).

Contaminated sites and spills can also serve as ongoing sources of PFAS, which can continue to leach into the environment over time (Breitmeyer *et al.*,2023). Determining the sources and emission pathways of PFAS is crucial for developing effective mitigation strategies, implementing appropriate regulations, and addressing the widespread environmental contamination caused by these persistent chemicals (Okafor *et al.*, 2023). Non-point sources increase pressure by raising PFAS levels in the environment, such as runoffs, grease-proofing coatings, incinerating non-stick cooking ware, carpets, strain-resistant fabrics, and aviation hydraulic fluids.

Waste water processing also releases PFAS and associated precursors due to hydrophobicity, leaving untreated short-chain PFAS in effluents (Rafiei & Nejadhashemi, 2023).

**3.1 Physical properties of per- and poly-fluoroalkyl substances**

PFAS are a type of polymer with a unique structure consisting of a fluorinated carbon chain. These chains are highly resistant to thermal, chemical, and biological degradation due to their strong carbon-fluorine bonds (Yadav *et al.*,2022). They are hydrophobic and oleophobic, making them effective as surfactants, repellents, and water/oil-resistant coatings (Das & Ronen, 2022).

PFAS have high thermal stability, allowing them to withstand high temperatures without decomposing (DiStefano *et al.*,2022). They are also chemically inert, resistant to hydrolysis, oxidation, and reduction, contributing to their persistence in the environment and ability to bioaccumulate in living organisms (Aly *et al.*,2022). Their low surface tension allows them to spread and coat surfaces effectively, making them useful in firefighting foams, stain-resistant coatings, and non-stick surfaces. PFAS, particularly long-chain varieties, have a high degree of bioaccumulation in living organisms and are highly persistent in the environment due to their chemical stability, low biodegradability, and resistance to metabolic breakdown (Hofer *et al.*,2021).

**3.2 Chemical properties of per- and poly-fluoroalkyl substances**

PFAS, or perfluoroalkyl carboxylic acids, are characterized by their strong and stable carbon-fluorine bonds due to the electronegativity difference between carbon and fluorine atoms (Lu *et al.*,2020). These bonds are highly polar, contributing to their unique properties. PFAS are considered strong acids due to the electron-withdrawing effect of the fluorinated carbon chain, which can influence their behavior in the environment and interactions with biological systems (Kadri *et al.*,2017). PFAS are effective surfactants, lowering surface tension and facilitating surface spreading and wetting.

Solubility and phase behavior of PFAS in water and organic solvents can vary significantly, with some being more water-soluble and longer-chain PFAS being less soluble in water but more soluble in organic solvents (Qi *et al.*,2022). PFAS are generally thermally stable and resistant to chemical reactions, but some can undergo thermal or chemical degradation under specific conditions, potentially leading to the formation of other PFAS or breakdown products (Jin *et al.*,2023). The persistence of PFAS in the environment and living organisms is a major concern regarding their potential long-term exposure and environmental impact.

**Table 3.1 Summary of the physicochemical properties of per- and poly-fluoroalkyl substances**

| Name | CAS | Solubility in water (mg/L) | Melting point ($^0$C) | Boiling point ($^0$C) | Vapour pressure (pa) | Log Pow | Log Koc |
|---|---|---|---|---|---|---|---|
| PFOS, Perfluorooctane sulfonic acid | 176-23-1 | 519-770 | | | $3.31\times10^{-4}$ | 5.5-7.03 | 5.57-3.3 |
| PFOA, Perfluorooctanoic acid | 335-67-1 | 3400 | | | 12.1 | 3.6 | 2.11 |
| PFHxS, Perfluorohexane sulfonic acid | 355-46-4 | 243.4 | 190 | 452 | $1.08\times10^{-6}$ | 2.2 | 3.36/2.14 |
| PFHxA, Perfluorohexanoic acid | 307-24-4 | 29.5 | | | 121 | 2.5 (3.12-3.26) | |
| PFHxA, Perfluorohexanoate, Sodium salt | 2923-26-4 | 29.5 | | | ~ 0 | 0.70 | |
| PFPeS, Perfluoropentane Sulfonic acid | 2706-91-4 | | | | | | |
| PFPeA, Perfluoropentanoic acid | 2706-90-3 | 120 | | | | 1.98 | |
| PFBS, Perfluorobutane sulfonate, potassium salt | 29420-90-3 | 4340 | 188 | 447 | $1.49\times10^{-6}$ | 0.26 | 2.25/1.07 |
| PFBA, Perfluorobutanoic acid | 375-22-4 | 447 | | | | 1.43 | |
| 8:2 FTOH, Fluorotelomer alcohol | 678-39-7 | 0.2 – 0.3 | | | 1.64 | 5.58 | 4.13 |
| 6:2 FTOH, Fluorotelomer alcohol | 647-42-7 | 19 | | | 22.1 | 4.54 | 2.43 |
| 4:2 FTOH, Fluorotelomer alcohol | 2043-47-2 | 97 | -44 | 113 | 1330 | 3.07/3.30 | 2.34/2.83 |
| 6:2 FTS, Fluorotelomer sulfonamide | 27619-97-2 | | | | | 3.47 – 3.98 | |
| 6:2 FTAC, Fluorotelomer acrylate | 17527-29-6 | 0.38 | | | 44.3 | 5.2 | |

(Fisheries and Oceans Canada, 2012**,** Sasaki *et al.*, 2011**,** Nakajigo *et al.*, 2024)

*Abbreviations; CAS - Chemical Abstracts Service Registry Number, Pow - 1-octanol/water partition coefficient, Koc - organic carbon partitioning coefficient.*

**3.3 Environmental fate of PFAS in the environment**

PFAS, particularly long-chain varieties, are highly persistent in the environment due to their carbon-fluorine bonds, allowing them to be transported long distances through various environmental media (Amin *et al.*,2023). This long-range transport potential allows them to be detected in remote areas. PFAS' environmental distribution is influenced by their physicochemical properties, which can be partitioned between different environmental compartments (Alesio *et al.*,2022). Bioaccumulation and biomagnification have a high potential for PFAS in living organisms, with higher concentrations observed in predators and top consumers in the food chain (Karimi Douna & Yousefi, 2023). This can lead to significant PFAS exposure and potential health risks for wildlife and humans who consume contaminated food sources.

PFAS are generally resistant to natural degradation processes, but some limited transformation can occur through mechanisms like photolysis, microbial degradation, and chemical reactions (Lucas *et al.*,2023). Understanding the transformation and degradation of PFAS is crucial for predicting their environmental fate and potential impacts. Multimedia contamination and exposure can lead to multiple exposure pathways for humans and wildlife, making the assessment and management of PFAS risks more challenging (Cousins *et al.*,2020).

### 3.4 Environmental transport of per- and poly-fluoroalkyl substances

Per- and polyfluoroalkyl substances (PFAS) are transported in various environmental compartments, including water, soil, sediment, air, and biota, based on their physicochemical properties (Aly *et al.*,2022). Factors such as water solubility, sorption to organic matter, and volatility influence the partitioning behavior of PFAS, determining their transport pathways and distribution (Lenka *et al.*,2023). PFAS are highly mobile in water and can easily leach into groundwater, contaminating surface water bodies. Surface water and groundwater transport are crucial for their widespread distribution. Atmospheric transport and deposition contribute to the global distribution of PFAS, even in remote areas (Kewalramani *et al.*,2022).

PFAS can adsorb to soil and sediment particles, facilitating their movement from terrestrial to aquatic environments. Soil erosion and sediment transport facilitate the movement of PFAS from terrestrial to aquatic environments (Groffen *et al.*,2023). PFAS in soil and sediment can also be remobilized and transported through processes like resuspension, bioturbation, and groundwater-surface water interactions. PFAS can bioaccumulate in living organisms and be transported through food webs and trophic levels and migratory behavior of animals and aquatic organisms contribute to the transport of PFAS between different ecosystems (Berhanu *et al.*,2023). Long-range transport of PFAS is possible due to their persistent and mobile nature, allowing them to be transported over long distances, often across national and regional boundaries (Kurwadkar *et al.*,2022). This long-range transport potential has led to the detection of PFAS in remote locations, far from their primary sources of release.

### 3.5 Processes influencing the Environmental transportation of PFAS

Adsorption is the binding of PFAS to solid surfaces, such as soil, sediment, or organic matter, influenced by the physicochemical properties of the compound, the adsorbent material, and environmental factors like pH and ionic strength (Izquierdo *et al.*,2023). Shorter-chain PFAS have lower adsorption, while longer-chain PFAS have a higher propensity to adsorb to solids (Costello & Lee, 2020). Adsorption limits the mobility of PFAS in the environment and influences their transport through water and soil systems (Sleep *et al.*,2023).

Volatilization is the process by which PFAS transition from liquid or solid phase to gas phase, depending on their vapor pressure. Factors affecting volatilization include temperature, wind, and the nature of the PFAS-containing matrix (Sima & Jaffé, 2021). The volatilized PFAS can be transported through the atmosphere and potentially deposited elsewhere. Leaching is the process by which PFAS are dissolved and transported through the soil or aquifer system, typically by water percolation (Bolan et al., 2021). Leaching can lead to contamination of groundwater and surface water systems, facilitating the transport of PFAS in the environment (Evangelou & Robinson, 2022).

Bio-transport refers to the movement of PFAS through the food web and biota, such as the migration of animals or uptake and accumulation in living organisms (Ateş *et al.*,2023). PFAS can bioaccumulate and bio-magnify in the food chain, leading to higher concentrations in predators and top consumers, this transformation and degradation of PFAS are important for predicting their environmental fate and potential impacts (Kleywegt *et al.*,2020).

**PFAS exposure pathways**

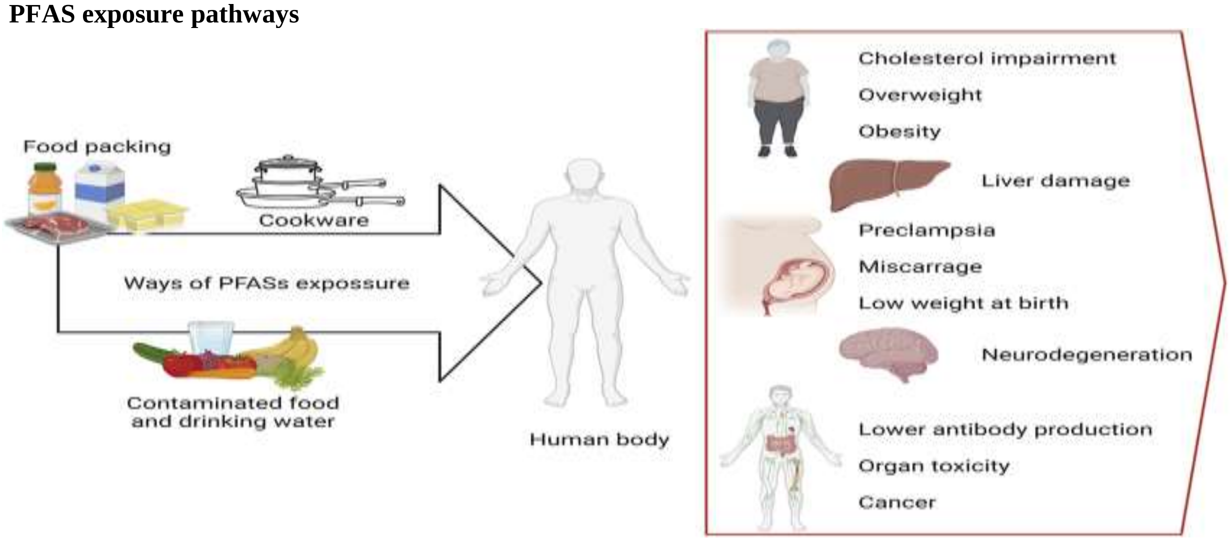


***Figure 3.1:*** *How humans are exposed to per- and poly-fluoroalkyl substances* (Araújo *et al.,* 2022)

PFAS can contaminate surface water and groundwater sources used for drinking water, with ingestion being the most significant exposure pathway for the general population. Food consumption exposure is another significant route, with PFAS bioaccumulating and biomagnifying up the food chain, leading to higher levels in foods grown or raised in PFAS-contaminated areas (Gaber *et al.*, 2023). PFAS can also contaminate food packaging materials, transferring these substances into food. Inhalation exposure is another significant exposure pathway, especially for individuals living near PFAS-contaminated sites or working in industries that use these substances (Dauchy, 2023). Exposure levels can be higher in occupational settings, such as firefighting, where PFAS-containing foams are used.

Dermal absorption exposure occurs through direct contact with PFAS-contaminated materials or products, particularly in occupational settings like firefighting (Izquierdo *et al.*, 2023). PFAS-containing consumer products, such as stain-resistant fabrics, non-stick cookware, water-repellent clothing, and personal care products, can also lead to exposure through dermal contact, inhalation, or inadvertent ingestion (McAdam & Bell, 2023). Dust ingestion exposure is another significant pathway, with PFAS accumulating in household dust, especially in homes or workplaces where PFAS-containing products are used or where PFAS-contaminated soil or water is present (Stecconi *et al.*, 2024). Ingestion of PFAS-contaminated dust, particularly by young children, can contribute to human exposure, especially for individuals living in PFAS-contaminated areas or those with high-dust environments (Zhao et al., 2023).

### 3.6 Health effects of exposure to per- and poly-fluoroalkyl substances

#### 3.6.1 Human exposure to PFAS

Prenatal exposure to polyphenols (PFAS) has been linked to various health issues, including reduced fetal growth, lower birth weight, and smaller head circumference (Goin *et al.,* 2022). It has also been associated with delayed puberty, altered sex hormone levels, and reduced fertility in both men and women. PFAS exposure can increase liver enzymes, leading to liver damage and potentially non-alcoholic fatty liver disease (Ilmiawati *et al.,* 2023). It can also increase cholesterol and lipid metabolism, increasing the risk of cardiovascular disease and related health problems. PFAS exposure has been linked to decreased vaccine antibody responses, suggesting potential immunotoxicity (Post, 2021).

Some studies have found associations between PFAS exposure and increased risk of infectious diseases and autoimmune disorders. PFAS can interfere with the endocrine system, leading to hormonal imbalances, altered thyroid hormone levels, and impacts on the reproductive system (Merrill *et al.,* 2022). Certain PFAS, particularly PFOA, have been associated with an increased risk of testicular and kidney cancer, with PFOA being classified as possibly carcinogenic to humans by the International Agency for Research on Cancer (IARC) (De Faria & Della Rosa, 2004). Other health effects include increased risk of high blood pressure, preeclampsia, ulcerative colitis, and potential neurological and cognitive effects (Mahoney *et al.,* 2022).

#### 3.6.2 Aquatic organisms and animals' exposure to PFAS

PFAS exposure poses significant threats to aquatic and terrestrial organisms, causing mortality, growth inhibition, and developmental abnormalities in fish species. Certain PFAS, such as PFOS and PFOA, can bioaccumulate in fish, leading to higher concentrations at higher trophic levels (Ehsan *et al.,* 2023). Aquatic invertebrates, such as crustaceans and mollusks, also suffer from reduced survival, growth, and reproduction. Amphibians, such as frogs and salamanders, experience impaired growth and development, while PFAS can affect their immune system and behavioral changes (Brunn *et al.,* 2023). Wildlife, including birds, mammals, and reptiles, suffer from liver damage, reproductive issues, and immunotoxicity due to bioaccumulation and biomagnification (Hamid *et al.,* 2023). Domestic animals, including livestock and pets, also suffer from liver and kidney damage, thyroid disruption, and reproductive issues. PFAS contamination can have broader ecological impacts, affecting food web dynamics, biodiversity, and overall ecosystem health. Disruption of sensitive species and changes in community structure can lead to cascading effects throughout the ecosystem (McGarr *et al.,* 2023).

#### 3.6.3 Plants' exposure to PFAS

PFAS, or poly-fluoroacetic acid, can be absorbed by plants from contaminated soil, water, or air, accumulating in various plant tissues like roots, stems, leaves, and fruits (Thompson *et al.*, 2023). The uptake and bioaccumulation of PFAS depend on factors like the type, plant species, and environmental conditions. Exposure to PFAS can negatively impact plant growth and development, leading to reduced seed germination, altered flowering and reproductive processes, and disruption of photosynthesis (Wang *et al.*, 2023). PFAS can also cause nutrient imbalance and oxidative stress, leading to increased susceptibility to pests and diseases. PFAS can be directly toxic to plants, causing visible symptoms like leaf chlorosis, necrosis, and wilting at high concentrations (Ngweme *et al.,* 2021). PFAS-contaminated plants can transfer the compounds up the food chain, leading to bioaccumulation in higher trophic levels, including animals and humans (Ogbuewu & Nnaji, 2023). This can have broader implications for the health and functioning of terrestrial and aquatic ecosystems, as PFAS exposure may affect the growth and productivity of primary producers and disrupt the entire food web (Nason *et al.,* 2024).

### 3.7 Regulatory guidelines of per- and polyfluoroalkyl substances

The U.S. Environmental Protection Agency (EPA) has established health advisory levels for PFOA and PFOS in drinking water, and has issued a PFAS Strategic Roadmap to address contamination (Ling *et al.,* 2024). The European Union has taken a comprehensive approach to PFAS regulation, focusing on restricting the use and production of certain PFAS under the REACH regulation (Garcia-Garin *et al.*, 2023). The European Food Safety Authority (EFSA) has set tolerable weekly intake levels for PFOA and PFOS to protect public health.

International conventions, such as the Stockholm Convention on Persistent Organic Pollutants, have listed PFOA, its salts, and PFOA-related compounds as persistent organic pollutants (POPs) subject to global restrictions and phase-out (Sonne *et al.*, 2023). The OECD/UNEP Global PFC Group has developed guidance and recommendations for the safe management of PFAS.A growing trend towards a class-based approach to PFAS regulation is emerging, with jurisdictions like the EU and some U.S. states considering or implementing regulations that group PFAS based on structural similarities and environmental persistence (OECD/UNEP Global PFC Group, 2015). This approach aims to address the wide variety of PFAS compounds and their potential cumulative risks. Regulatory guidelines often include requirements for reliable analytical methods and monitoring programs to detect and quantify PFAS in environmental media and human biomonitoring samples. Standardized analytical methods, such as those developed by the EPA and other organizations, are essential for consistent and accurate PFAS measurements (Winchell *et al.*, 2021).

### 3.8 Emerging trends and future directions of per- and polyfluoroalkyl substances

The global trend towards phasing out long-chain PFAS (polyfluoroacetic acids) due to their persistent and bio-accumulative nature has led to the development and increased use of shorter-chain PFAS as alternatives (Lee et al., 2022). Governments and international organizations are developing and implementing regulations to restrict the use of PFAS, aiming to limit environmental release and human exposure (McDonough *et al.*, 2021). Examples include the PFAS Action Plan in the United States and the REACH regulation in the European Union (Parolini *et al.*, 2022).

Expansion of PFAS monitoring and research is also being emphasized, with researchers developing more comprehensive analytical methods to detect and quantify a wider range of PFAS compounds (B. F. da Silva *et al.*, 2022). Advancements in PFAS remediation and destruction technologies, such as adsorption, membrane filtration, advanced oxidation processes, and thermal destruction methods, are being developed to mitigate environmental contamination and human exposure (Garg *et al.*, 2023).

Evaluation of toxicity and potential health effects associated with exposure to PFAS is also being conducted, with a focus on developing non-fluorinated or inherently degradable compounds (Rericha *et al.*, 2023). Successful substitution of PFAS in various applications is crucial for reducing environmental and human exposure in the long term. Efforts are underway to improve the lifecycle management of PFAS-containing products, including responsible disposal, recycling, and waste treatment. The concept of a circular economy, where PFAS are recovered and reused, is being explored to minimize the release of these substances into the environment (Bulson *et al.*, 2023).

### 3.9 Recent advancements in source apportionment and biodegradation research

Advanced analytical techniques, such as high-resolution mass spectrometry and targeted/non-targeted analysis, have enabled more comprehensive identification and characterization of PFAS compounds in environmental samples (Silva *et al.*, 2021). Researchers are using fingerprinting and profiling to differentiate and apportion PFAS sources, such as industrial, municipal, or agricultural inputs (Wang *et al.*, 2023). Multivariate statistical analyses, principal component analysis, and receptor modeling are employed to quantify the relative contributions of different PFAS sources in the environment. Isotopic analysis, using stable techniques like carbon and fluorine isotopes, provides additional insights into the origins and transformation processes of PFAS (Barhoumi *et al.*, 2019).

Biotransformation pathways are being investigated, with studies identifying enzymes and microbial consortia that can initiate the breakdown of PFAS (Jin et al., 2023). Co-metabolic processes are also being explored, with the presence of other carbon sources or co-substrates enhancing microbial transformation. Transformation byproducts are also being investigated, which can be equally or more persistent and toxic than the parent PFAS compounds (Bankole *et al.*, 2022). Field-scale applications include pilot-scale demonstrations of various remediation technologies, comprehensive monitoring and verification, and integrated approaches to address PFAS contamination holistically and effectively (Vu & Wu, 2022).

Researchers have developed advanced methods for apportioning PFAS (Perfluoroalkyl Acids) in various environments. These methods use multiple PFAS compounds as "tracers" to differentiate between different sources, such as industrial, firefighting, or wastewater-related inputs (Charbonnet *et al.*, 2021). Isotopic analysis, particularly carbon and fluorine isotopes, has emerged as a powerful tool for source identification and apportionment (Ren *et al.*, 2022). Studies have also focused on analyzing spatial and temporal trends of PFAS in environmental media, such as water, soil, and sediment, to identify hotspots, track the evolution of PFAS sources and transport over time, and differentiate between legacy and ongoing inputs (Rehman *et al.*, 2023). Advanced receptor modeling techniques, such as positive matrix factorization and chemical mass balance models, have been applied to quantify the contributions of different source categories to the overall PFAS burden in a particular environment (Ren *et al.*, 2023).

Researchers have made progress in elucidating the complex microbial biotransformation pathways for certain PFAS, particularly the shorter-chain perfluoroalkyl acids. Engineered bioremediation approaches, such as the use of specialized microbial consortia or the stimulation of indigenous microbial communities, have been explored to enhance the degradation of PFAS in contaminated environments (Wasfi *et al.*, 2023). Cometabolic degradation of PFAS is also being investigated, where the transformation of these compounds is facilitated by the presence of other, more easily degradable substrates. Anaerobic processes, particularly for the transformation of perfluoroalkyl carboxylates and sulfonates, have also been highlighted (Izawa *et al.*, 2021).

This review on PFAS compounds focuses on understanding their distribution, exposure pathways, and the risks they pose to ecosystems and human health. Long-range atmospheric transport, deposition in remote areas, and combined effects of PFAS mixtures are critical for predicting contamination and assessing risks (Chen *et al.*, 2023). Analytical techniques for detecting PFAS, alongside large-scale epidemiological studies, are needed to better link exposure to health effects (Park *et al.*, 2021). Developing efficient, scalable, and cost-effective removal methods, particularly during wastewater and sludge treatment, is essential for managing and mitigating PFAS pollution.

## 4.0 Discussion, conclusion, and recommendations

### 4.1 Discussion

Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals used in various industries due to their water- and oil-repellent properties. Understanding their source apportionment is crucial for effective remediation strategies, as these compounds can persist in the environment and pose significant health risks. Key sources of PFAS contamination include industrial discharges, wastewater effluent, and firefighting foams. Studies using source tracking methods have identified distinct PFAS profiles associated with different sources, enabling more targeted regulatory actions. PFAS's biodegradation pathways are complex due to their stable carbon-fluorine bonds, making them resistant to conventional degradation processes. Recent research has identified potential biotic and abiotic pathways for PFAS degradation, including microbial metabolism, photolysis, and hydrolysis. Enzymatic pathways, particularly those involving fluorinated alkane-oxidizing bacteria, are under investigation for their potential to break down PFAS. However, knowledge gaps persist, and further exploration is needed to assess the environmental fate of PFAS compounds and the interaction between PFAS and other environmental contaminants. Future research should focus on elucidating PFAS biodegradation mechanisms and integrating source apportionment data with biodegradation studies to develop comprehensive management strategies for PFAS contamination.

### 4.2 Conclusion

The review highlights the complexity of PFAS source apportionment, revealing contributions from industrial applications, consumer products, and environmental persistence. Effective management of PFAS contamination requires a comprehensive understanding of these sources to inform regulatory measures and remediation strategies. Proposed biodegradation pathways offer insights into potential bioremediation techniques. Advancements in microbial and enzymatic degradation research present viable avenues for reducing PFAS concentrations. A concerted effort combining source identification, innovative biodegradation approaches, and stakeholder collaboration is essential.

### 5.3 Recommendations

The plan involves enhancing source identification of PFAS contamination, establishing stricter regulations for production and use, investing in research to understand PFAS biodegradation mechanisms, developing bioremediation strategies, increasing public awareness about PFAS sources and risks, fostering interdisciplinary collaboration among researchers, policymakers, and industry stakeholders, establishing long-term environmental monitoring programs to track PFAS levels, and promoting alternative substance development to reduce reliance on persistent chemicals. The plan also includes investing in research to understand microbial strains and enzymatic pathways, developing bioremediation technologies, increasing public engagement, fostering interdisciplinary collaboration, and promoting long-term environmental monitoring programs to track PFAS levels.

## References

Al Amin, M., Luo, Y., Nolan, A., Mallavarapu, M., Naidu, R., & Fang, C. (2023). Thermal kinetics of PFAS and precursors in soil: Experiment and surface simulation in temperature-time plane. *Chemosphere*, *318*. https://doi.org/10.1016/j.chemosphere.2023.138012

Alesio, J. L., Slitt, A., & Bothun, G. D. (2022). Critical new insights into the binding of poly- and perfluoroalkyl substances (PFAS) to albumin protein. *Chemosphere*, *287*. https://doi.org/10.1016/j.chemosphere.2021.131979

Aly, N. A., Dodds, J. N., Luo, Y. S., Grimm, F. A., Foster, M. K., Rusyn, I., & Baker, E. S. (2022). Utilizing ion mobility spectrometry-mass spectrometry for the characterization and detection of persistent organic pollutants and their metabolites. *Analytical and Bioanalytical Chemistry*, *414*(3). https://doi.org/10.1007/s00216-021-03686-w

Araújo, R. G., Rodríguez-Hernandéz, J. A., González-González, R. B., Macias-Garbett, R., Martínez-Ruiz, M., Reyes-Pardo, H., Hernández Martínez, S. A., Parra-Arroyo, L., Melchor-Martínez, E. M., Sosa-Hernández, J. E., Coronado-Apodaca, K. G., Varjani, S., Barceló, D., Iqbal, H. M. N., & Parra-Saldívar, R. (2022). Detection and Tertiary Treatment Technologies of Poly- and Perfluoroalkyl Substances in Wastewater Treatment Plants. In *Frontiers in Environmental Science* (Vol. 10). https://doi.org/10.3389/fenvs.2022.864894

Ateş, A., Lattimer, B. Y., & Conversano, V. (2023). Fuel effects on foams generated using different surfactants. *Fire Safety Journal*, *141*. https://doi.org/10.1016/j.firesaf.2023.104012

Bankole, P. O., Taghoghor Omoni, V., Mulla, S. I., Adebajo, S. O., & Adekunle, A. A. (2022). Co-biomass degradation of fluoranthene by marine-derived fungi; Aspergillus aculeatus and Mucor irregularis: Comprehensive process optimization, enzyme induction and metabolic analyses. *Arabian Journal of Chemistry*, *15*(9). https://doi.org/10.1016/j.arabjc.2022.104036

Barhoumi, B., Beldean-Galea, M. S., Al-Rawabdeh, A. M., Roba, C., Martonos, I. M., Bălc, R., Kahlaoui, M., Touil, S., Tedetti, M., Driss, M. R., & Baciu, C. (2019). Occurrence, distribution and ecological risk of trace metals and organic pollutants in surface sediments from a Southeastern European river (Someşu Mic River, Romania). *Science of the Total Environment*, *660*. https://doi.org/10.1016/j.scitotenv.2018.12.428

Berg, C., Crone, B., Gullett, B., Higuchi, M., Krause, M. J., Lemieux, P. M., Martin, T., Shields, E. P., Struble, E., Thoma, E., & Whitehill, A. (2022). Developing innovative treatment technologies for PFAS-containing wastes. In *Journal of the Air and Waste Management Association* (Vol. 72, Issue 6). https://doi.org/10.1080/10962247.2021.2000903

Berhanu, A., Mutanda, I., Taolin, J., Qaria, M. A., Yang, B., & Zhu, D. (2023). A review of microbial degradation of per- and polyfluoroalkyl substances (PFAS): Biotransformation routes and enzymes. In *Science of the Total Environment* (Vol. 859). https://doi.org/10.1016/j.scitotenv.2022.160010

Bolan, N., Sarkar, B., Vithanage, M., Singh, G., Tsang, D. C. W., Mukhopadhyay, R., Ramadass, K., Vinu, A., Sun, Y., Ramanayaka, S., Hoang, S. A., Yan, Y., Li, Y., Rinklebe, J., Li, H., & Kirkham, M. B. (2021). Distribution, behaviour, bioavailability and remediation of poly- and per-fluoroalkyl substances (PFAS) in solid biowastes and biowaste-treated soil. *Environment International*, *155*. https://doi.org/10.1016/j.envint.2021.106600

Breitmeyer, S. E., Williams, A. M., Duris, J. W., Eicholtz, L. W., Shull, D. R., Wertz, T. A., & Woodward, E. E. (2023). Per- and polyfluorinated alkyl substances (PFAS) in Pennsylvania surface waters: A statewide assessment, associated sources, and land-use relations. *Science of the Total Environment*, *888*. https://doi.org/10.1016/j.scitotenv.2023.164161

Brunn, H., Arnold, G., Körner, W., Rippen, G., Steinhäuser, K. G., & Valentin, I. (2023). PFAS: forever chemicals—persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites. In *Environmental Sciences Europe* (Vol. 35, Issue 1). https://doi.org/10.1186/s12302-023-00721-8

Bulson, E. E., Remucal, C. K., & Hicks, A. L. (2023). End-of-life circulation of PFAS in metal recycling streams: A sustainability-focused review. In *Resources, Conservation and Recycling* (Vol. 194). https://doi.org/10.1016/j.resconrec.2023.106978

Burkhard, L. P., & Votava, L. K. (2023). Review of per- and polyfluoroalkyl substances (PFAS) bioaccumulation in earthworms. In *Environmental Advances* (Vol. 11). https://doi.org/10.1016/j.envadv.2022.100335

Caban-Martinez, A. J., Feliciano, P. L., Oduwole, S., Solle, N. S., Gonzalez-Umana, C., Stone, T., & Kobetz, E. N. (2022). Abstract 25: Per- and polyfluoroalkyl substances and obesity in Florida firefighters. *Cancer Research*, *82*(12_Supplement). https://doi.org/10.1158/1538-7445.am2022-25

Charbonnet, J. A., Rodowa, A. E., Joseph, N. T., Guelfo, J. L., Field, J. A., Jones, G. D., Higgins, C. P., Helbling, D. E., & Houtz, E. F. (2021). Environmental Source Tracking of Per- And Polyfluoroalkyl Substances within a Forensic Context: Current and Future Techniques. *Environmental Science and Technology*, *55*(11). https://doi.org/10.1021/acs.est.0c08506

Chen, Y., Wei, L., Luo, W., Jiang, N., Shi, Y., Zhao, P., Ga, B., Pei, Z., Li, Y., Yang, R., & Zhang, Q. (2023). Occurrence, spatial distribution, and sources of PFASs in the water and sediment from lakes in the Tibetan Plateau. *Journal of Hazardous Materials*, *443*. https://doi.org/10.1016/j.jhazmat.2022.130170

Costello, M. C. S., & Lee, L. S. (2020). Sources, Fate, and Plant Uptake in Agricultural Systems of Per- and Polyfluoroalkyl Substances. In *Current Pollution Reports*. https://doi.org/10.1007/s40726-020-00168-y

Cousins, I. T., Dewitt, J. C., Glüge, J., Goldenman, G., Herzke, D., Lohmann, R., Ng, C. A., Scheringer, M., & Wang, Z. (2020). The high persistence of PFAS is sufficient for their management as a chemical class. In *Environmental Science: Processes and Impacts* (Vol. 22, Issue 12). https://doi.org/10.1039/d0em00355g

da Silva, B. F., Aristizabal-Henao, J. J., Aufmuth, J., Awkerman, J., & Bowden, J. A. (2022). Survey of per- and polyfluoroalkyl substances (PFAS) in surface water collected in Pensacola, FL. *Heliyon*, *8*(8). https://doi.org/10.1016/j.heliyon.2022.e10239

Das, S., & Ronen, A. (2022). A Review on Removal and Destruction of Per-and Polyfluoroalkyl Substances (PFAS) by Novel Membranes. In *Membranes* (Vol. 12, Issue 7). https://doi.org/10.3390/membranes12070662

Dauchy, X. (2023). Evidence of large-scale deposition of airborne emissions of per- and polyfluoroalkyl substances (PFASs) near a fluoropolymer production plant in an urban area. *Chemosphere*, *337*. https://doi.org/10.1016/j.chemosphere.2023.139407

De Faria, P. M., & Della Rosa, H. V. (2004). Determinação do 1-hidroxipireno em amostras de urina por cromnatografia líquida de alta eficiência - Estudo dos parâmetros de validação. *Revista Brasileira de Ciencias Farmaceuticas/Brazilian Journal of Pharmaceutical Sciences*, *40*(2). https://doi.org/10.1590/s1516-93322004000200015

De Silva, A. O., Armitage, J. M., Bruton, T. A., Dassuncao, C., Heiger-Bernays, W., Hu, X. C., Kärrman, A., Kelly, B., Ng, C., Robuck, A., Sun, M., Webster, T. F., & Sunderland, E. M. (2021). PFAS Exposure Pathways for Humans and Wildlife: A Synthesis of Current Knowledge and Key Gaps in Understanding. In *Environmental Toxicology and Chemistry* (Vol. 40, Issue 3). https://doi.org/10.1002/etc.4935

DiStefano, R., Feliciano, T., Mimna, R. A., Redding, A. M., & Matthis, J. (2022). Thermal destruction of PFAS during full-scale reactivation of PFAS-laden granular activated carbon. *Remediation*, *32*(4). https://doi.org/10.1002/rem.21735

Ehsan, M. N., Riza, M., Pervez, M. N., Khyum, M. M. O., Liang, Y., & Naddeo, V. (2023). Environmental and health impacts of PFAS: Sources, distribution and sustainable management in North Carolina (USA). In *Science of the Total Environment* (Vol. 878). https://doi.org/10.1016/j.scitotenv.2023.163123

Evangelou, M. W. H., & Robinson, B. H. (2022). The Phytomanagement of PFAS-Contaminated Land. In *International Journal of Environmental Research and Public Health* (Vol. 19, Issue 11). https://doi.org/10.3390/ijerph19116817

Fisheries and Oceans Canada. (2012). Marine Protected Area Network Planning in the Scotian Shelf Bioregion: Objectives, Data, and Methods. *Canadian Science Advisory Secretariat Science Advisory Report*, *2012/064*.

Gaber, N., Bero, L., & Woodruff, T. J. (2023). The Devil they Knew: Chemical Documents Analysis of Industry Influence on PFAS

Science. *Annals of Global Health*, *89*(1). https://doi.org/10.5334/aogh.4013

Garcia-Garin, O., Borrell, A., Colomer-Vidal, P., Vighi, M., Trilla-Prieto, N., Aguilar, A., Gazo, M., & Jiménez, B. (2023). Biomagnification and temporal trends (1990–2021) of perfluoroalkyl substances in striped dolphins (Stenella coeruleoalba) from the NW Mediterranean sea. *Environmental Pollution*, *339*. https://doi.org/10.1016/j.envpol.2023.122738

Garg, A., Shetti, N. P., Basu, S., Nadagouda, M. N., & Aminabhavi, T. M. (2023). Treatment technologies for removal of per- and polyfluoroalkyl substances (PFAS) in biosolids. In *Chemical Engineering Journal* (Vol. 453). https://doi.org/10.1016/j.cej.2022.139964

Goin, D. E., Abrahamsson, D., Wang, M., Jiang, T., Park, J. S., Sirota, M., Morello-Frosch, R., DeMicco, E., Zlatnik, M. G., & Woodruff, T. J. (2022). Disparities in chemical exposures among pregnant women and neonates by socioeconomic and demographic characteristics: A nontargeted approach. *Environmental Research*, *215*. https://doi.org/10.1016/j.envres.2022.114158

Griffin, E. K., Hall, L. M., Brown, M. A., Taylor-Manges, A., Green, T., Suchanec, K., Furman, B. T., Congdon, V. M., Wilson, S. S., Osborne, T. Z., Martin, S., Schultz, E. A., Holden, M. M., Lukacsa, D. T., Greenberg, J. A., Deliz Quiñones, K. Y., Lin, E. Z., Camacho, C., & Bowden, J. A. (2023). Aquatic Vegetation, an Understudied Depot for PFAS. *Journal of the American Society for Mass Spectrometry*, *34*(9). https://doi.org/10.1021/jasms.3c00018

Groffen, T., Prinsen, E., Devos Stoffels, O. A., Maas, L., Vincke, P., Lasters, R., Eens, M., & Bervoets, L. (2023). PFAS accumulation in several terrestrial plant and invertebrate species reveals species-specific differences. *Environmental Science and Pollution Research*, *30*(9). https://doi.org/10.1007/s11356-022-23799-8

Hamid, N., Junaid, M., Manzoor, R., Sultan, M., Chuan, O. M., & Wang, J. (2023). An integrated assessment of ecological and human health risks of per- and polyfluoroalkyl substances through toxicity prediction approaches. In *Science of the Total Environment* (Vol. 905). https://doi.org/10.1016/j.scitotenv.2023.167213

Hofer, T., Myhre, O., Peltola-Thies, J., & Hirmann, D. (2021). Analysis of elimination half-lives in MamTKDB 1.0 related to bioaccumulation: Requirement of repeated administration and blood plasma values underrepresent tissues. *Environment International*, *155*. https://doi.org/10.1016/j.envint.2021.106592

Ilmiawati, I., Mahata, L. E., Aliska, G., Rahmatini, R., Julizar, J., Katar, Y., Rustam, E., & Usman, E. (2023). Edukasi Masyarakat Mengenai Toksikan Abadi (Forever Chemicals) dalam Kosmetik Bersifat Waterproof. *Warta Pengabdian Andalas*, *30*(4). https://doi.org/10.25077/jwa.30.4.708-714.2023

Izawa, M., Sakai, M., Mori, J. F., & Kanaly, R. A. (2021). Cometabolic benzo[a]pyrene biotransformation by Sphingobium barthaii KK22 proceeds through the kata-annelated ring and 1-pyrenecarboxylic acid to downstream products. *Journal of Hazardous Materials Advances*, *4*. https://doi.org/10.1016/j.hazadv.2021.100018

Izquierdo, S., Pacheco, N., Durán-Valle, C. J., & López-Coca, I. M. (2023). From Waste to Resource: Utilizing Sweet Chestnut Waste to Produce Hydrothermal Carbon for Water Decontamination. *C-Journal of Carbon Research*, *9*(2). https://doi.org/10.3390/c9020057

Jin, B., Zhu, Y., Zhao, W., Liu, Z., Che, S., Chen, K., Lin, Y. H., Liu, J., & Men, Y. (2023). Aerobic Biotransformation and Defluorination of Fluoroalkylether Substances (ether PFAS): Substrate Specificity, Pathways, and Applications. *Environmental Science and Technology Letters*, *10*(9). https://doi.org/10.1021/acs.estlett.3c00411

Kadri, T., Rouissi, T., Kaur Brar, S., Cledon, M., Sarma, S., & Verma, M. (2017). Biodegradation of polycyclic aromatic hydrocarbons (PAHs) by fungal enzymes: A review. In *Journal of Environmental Sciences (China)* (Vol. 51). https://doi.org/10.1016/j.jes.2016.08.023

Karimi Douna, B., & Yousefi, H. (2023). Removal of PFAS by Biological Methods. *Asian Pacific Journal of Environment and Cancer*, *6*(1). https://doi.org/10.31557/apjec.2023.6.1.53-68

Kewalramani, J. A., Wang, B., Marsh, R. W., Meegoda, J. N., & Rodriguez Freire, L. (2022). Coupled high and low-frequency ultrasound remediation of PFAS-contaminated soils. *Ultrasonics Sonochemistry*, *88*. https://doi.org/10.1016/j.ultsonch.2022.106063

Kleywegt, S., Raby, M., McGill, S., & Helm, P. (2020). The impact of risk management measures on the concentrations of per- and polyfluoroalkyl substances in source and treated drinking waters in Ontario, Canada. *Science of the Total Environment*, *748*. https://doi.org/10.1016/j.scitotenv.2020.141195

Koban, L. A., & Pfluger, A. R. (2023). Per- and polyfluoroalkyl substances (PFAS) exposure through munitions in the Russia–Ukraine conflict. *Integrated Environmental Assessment and Management*, *19*(2). https://doi.org/10.1002/ieam.4672

Kurwadkar, S., Dane, J., Kanel, S. R., Nadagouda, M. N., Cawdrey, R. W., Ambade, B., Struckhoff, G. C., & Wilkin, R. (2022). Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution. In *Science of the Total Environment* (Vol. 809). https://doi.org/10.1016/j.scitotenv.2021.151003

Lee, K., Skinn, B., Snyder, S., Athmer, C., & Inman, M. (2022). Tandem Electrokinetic/Electrocatalytic Remediation of Pfas in Soils. *ECS Meeting Abstracts*, *MA2022-02*(58). https://doi.org/10.1149/ma2022-02582188mtgabs

Lenka, S. P., Kah, M., & Padhye, L. P. (2023). Losses of Ultrashort- and Short-Chain PFAS to Polypropylene Materials. *ACS ES and T Water*, *3*(8). https://doi.org/10.1021/acsestwater.3c00191

Ling, A. L., Vermace, R. R., McCabe, A. J., Wolohan, K. M., & Kyser, S. J. (2024). Is removal and destruction of perfluoroalkyl and polyfluoroalkyl substances from wastewater effluent affordable? *Water Environment Research*, *96*(1). https://doi.org/10.1002/wer.10975

Lu, D., Sha, S., Luo, J., Huang, Z., & Zhang Jackie, X. (2020). Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): A critical review. In *Journal of Hazardous Materials* (Vol. 386). https://doi.org/10.1016/j.jhazmat.2019.121963

Lucas, K., Gaines, L. G. T., Paris-Davila, T., & Nylander-French, L. A. (2023). Occupational exposure and serum levels of per- and polyfluoroalkyl substances (PFAS): A review. In *American Journal of Industrial Medicine* (Vol. 66, Issue 5). https://doi.org/10.1002/ajim.23454

Mahinroosta, R., & Senevirathna, L. (2020). A review of the emerging treatment technologies for PFAS contaminated soils. In *Journal of Environmental Management* (Vol. 255). https://doi.org/10.1016/j.jenvman.2019.109896

Mahoney, H., Xie, Y., Brinkmann, M., & Giesy, J. P. (2022). Next generation per- and poly-fluoroalkyl substances: Status and trends, aquatic toxicity, and risk assessment. In *Eco-Environment and Health* (Vol. 1, Issue 2). https://doi.org/10.1016/j.eehl.2022.05.002

May, P. A., Tabachnick, B. G., Phillip Gossage, J., Kalberg, W. O., Marais, A. S., Robinson, L. K., Manning, M. A., Blankenship, J., Buckley, D., Eugene Hoyme, H., & Adnams, C. M. (2013). Maternal factors predicting cognitive and behavioral characteristics of children with fetal alcohol spectrum disorders. *Journal of Developmental and Behavioral Pediatrics*, *34*(5). https://doi.org/10.1097/DBP.0b013e3182905587

McAdam, J., & Bell, E. M. (2023). Determinants of maternal and neonatal PFAS concentrations: a review. In *Environmental Health: A Global Access Science Source* (Vol. 22, Issue 1). https://doi.org/10.1186/s12940-023-00992-x

McDonough, J., Lang, J., & Anderson, J. (2021). The practicalities of fluorosurfactant firefighting foam transition: Equipment cleaning and fluorine free alternatives. *Proceedings of the Air and Waste Management Association's Annual Conference and Exhibition, AWMA, 2021-June*.

McGarr, J. T., Mbonimpa, E. G., McAvoy, D. C., & Soltanian, M. R. (2023). Fate and Transport of Per- and Polyfluoroalkyl Substances (PFAS) at Aqueous Film Forming Foam (AFFF) Discharge Sites: A Review. In *Soil Systems* (Vol. 7, Issue 2). https://doi.org/10.3390/soilsystems7020053

Merrill, A. K., Conrad, K., Marvin, E., & Sobolewski, M. (2022). Effects of gestational low dose perfluorooctanoic acid on maternal and "anxiety-like" behavior in dams. *Frontiers in Toxicology*, *4*. https://doi.org/10.3389/ftox.2022.971970

Nakajigo, J., Johansen, T. A., Kiberu, J. M., Jensen, E. H., & Tiberindwa, J. V. (2024). Prediction of reservoir properties using inverse rock physics modelling in the Kanywataba Exploration Area, Albertine Graben. *Petroleum Geoscience*, *30*(1). https://doi.org/10.1144/petgeo2023-031

Nakiyende, H., Basooma, A., Ikwaput Nyeko, J., Okello, W., Rugadya, R., Albrecht, C., Lawrence, T., Van Steenberge, M., Smith, S., Muderhwa, N., Matunguru, J., Mulongaibalu, M., & Ajode, M. Z. (2023). Limitations for informed decision making and better management of the transboundary Lake Albert fisheries resources. In *Journal of Great Lakes Research* (Vol. 49, Issue 6). https://doi.org/10.1016/j.jglr.2023.02.006

Nason, S. L., Thomas, S., Stanley, C., Silliboy, R., Blumenthal, M., Zhang, W., Liang, Y., Jones, J. P., Zuverza-Mena, N., White, J. C., Haynes, C. L., Vasiliou, V., Timko, M. P., & Berger, B. W. (2024). A comprehensive trial on PFAS remediation: hemp phytoextraction and PFAS degradation in harvested plants. *Environmental Science: Advances*, *3*(2). https://doi.org/10.1039/d3va00340j

Ngweme, G. N., Al Salah, D. M. M., Laffite, A., Sivalingam, P., Grandjean, D., Konde, J. N., Mulaji, C. K., Breider, F., & Poté, J. (2021). Occurrence of organic micropollutants and human health risk assessment based on consumption of Amaranthus viridis, Kinshasa in the Democratic Republic of the Congo. *Science of the Total Environment*, *754*. https://doi.org/10.1016/j.scitotenv.2020.142175

OECD/UNEP Global PFC Group. (2015). Risk reduction approaches for PFASs – a cross-country analysis. In *OECD Environment, Health and Safety Publications. Series on Risk Management* (Vol. 29, Issue 29).

Ogbuewu, I., & Nnaji, J. C. (2023). Human Health Impacts of Perfluoroalkyl Substances, Micro- and Nanoplastics Contamination of Drinking Water. *Archives of Ecotoxicology*, *5*(3). https://doi.org/10.36547/ae.2023.5.3.75-82

Okafor, V. N., Omokpariola, D. O., Obumselu, O. F., & Eze, C. G. (2023). Exposure risk to heavy metals through surface and groundwater used for drinking and household activities in Ifite Ogwari, Southeastern Nigeria. *Applied Water Science*, *13*(4). https://doi.org/10.1007/s13201-023-01908-3

Park, J., Hodges, K. L., Tumuluri, U., Zaki, A. A., Dussor, J. C., Daunis, T., Clark, K. P., Robbins, D. I., & Roodenko, K. (2021). *Infrared sensors for environmental and biomedical applications*. https://doi.org/10.1117/12.2583757

Parolini, M., De Felice, B., Rusconi, M., Morganti, M., Polesello, S., & Valsecchi, S. (2022). A review of the bioaccumulation and adverse effects of PFAS in free-living organisms from contaminated sites nearby fluorochemical production plants. In *Water Emerging Contaminants and Nanoplastics* (Vol. 1, Issue 4). https://doi.org/10.20517/wecn.2022.15

Pinkard, B. R., Austin, C., Purohit, A. L., Li, J., & Novosselov, I. V. (2023). Destruction of PFAS in AFFF-impacted fire training pit water, with a continuous hydrothermal alkaline treatment reactor. *Chemosphere*, *314*. https://doi.org/10.1016/j.chemosphere.2022.137681

Post, G. B. (2021). Recent US State and Federal Drinking Water Guidelines for Per- and Polyfluoroalkyl Substances. In *Environmental Toxicology and Chemistry* (Vol. 40, Issue 3). https://doi.org/10.1002/etc.4863

Qi, Y., Cao, H., Pan, W., Wang, C., & Liang, Y. (2022). The role of dissolved organic matter during Per- and Polyfluorinated Substance (PFAS) adsorption, degradation, and plant uptake: A review. In *Journal of Hazardous Materials* (Vol. 436). https://doi.org/10.1016/j.jhazmat.2022.129139

Rafiei, V., & Nejadhashemi, A. P. (2023). Watershed scale PFAS fate and transport model for source identification and management implications. *Water Research*, *240*. https://doi.org/10.1016/j.watres.2023.120073

Rehman, A. U., Crimi, M., & Andreescu, S. (2023). Current and emerging analytical techniques for the determination of PFAS in environmental samples. In *Trends in Environmental Analytical Chemistry* (Vol. 37). https://doi.org/10.1016/j.teac.2023.e00198

Ren, J., Fernando, S., Hopke, P. K., Holsen, T. M., & Crimmins, B. S. (2022). Suspect Screening and Nontargeted Analysis of Per- and Polyfluoroalkyl Substances in a Lake Ontario Food Web. *Environmental Science and Technology*, *56*(24). https://doi.org/10.1021/acs.est.2c04321

Ren, X., Yang, C., Zhao, B., Xiao, J., Gao, D., & Zhang, H. (2023). Water quality assessment and pollution source apportionment using multivariate statistical and PMF receptor modeling techniques in a sub-watershed of the upper Yangtze River, Southwest China. *Environmental Geochemistry and Health*, *45*(9). https://doi.org/10.1007/s10653-023-01477-z

Rericha, Y., Simonich, M. T., Truong, L., & Tanguay, R. L. (2023). Review of the zebrafish as a model to investigate per- and polyfluoroalkyl substance toxicity. In *Toxicological Sciences* (Vol. 194, Issue 2). https://doi.org/10.1093/toxsci/kfad051

Roth, K., & Petriello, M. C. (2022). Exposure to per- and polyfluoroalkyl substances (PFAS) and type 2 diabetes risk. In *Frontiers in Endocrinology* (Vol. 13). https://doi.org/10.3389/fendo.2022.965384

Sasaki, Y., Iwai, N., Kimura, O., Ono, S., Tsuda, T., & Deguchi, E. (2011). Establishment of a rescue program for anorectal malformations induced by retinoic acid in mice. *Journal of Pediatric Surgery*, *46*(7). https://doi.org/10.1016/j.jpedsurg.2010.10.011

Sharp, S., Sardiña, P., Metzeling, L., McKenzie, R., Leahy, P., Menkhorst, P., & Hinwood, A. (2021). Per- and Polyfluoroalkyl Substances in Ducks and the Relationship with Concentrations in Water, Sediment, and Soil. *Environmental Toxicology and Chemistry*, *40*(3). https://doi.org/10.1002/etc.4818

Sima, M. W., & Jaffé, P. R. (2021). A critical review of modeling Poly- and Perfluoroalkyl Substances (PFAS) in the soil-water environment. In *Science of the Total Environment* (Vol. 757). https://doi.org/10.1016/j.scitotenv.2020.143793

Sleep, J. A., Miklavcic, S. J., & Juhasz, A. L. (2023). Modelling of PFAS-surface interactions: Effect of surface charge and solution ions. *Chemosphere*, *319*. https://doi.org/10.1016/j.chemosphere.2023.137910

Sonne, C., Desforges, J. P., Gustavson, K., Bossi, R., Bonefeld-Jørgensen, E. C., Long, M., Rigét, F. F., & Dietz, R. (2023). Assessment of exposure to perfluorinated industrial substances and risk of immune suppression in Greenland and its global context: a mixed-methods study. *The Lancet Planetary Health*, *7*(7). https://doi.org/10.1016/S2542-5196(23)00106-7

Stecconi, T., Tavoloni, T., Stramenga, A., Bacchiocchi, S., Barola, C., Dubbini, A., Galarini, R., Moretti, S., Sagratini, G., & Piersanti, A. (2024). A LC-MS/MS procedure for the analysis of 19 perfluoroalkyl substances in food fulfilling recent EU regulations requests. *Talanta*, *266*. https://doi.org/10.1016/j.talanta.2023.125054

Stoiber, T., Evans, S., & Naidenko, O. V. (2020). Disposal of products and materials containing per- and polyfluoroalkyl substances (PFAS): A cyclical problem. In *Chemosphere* (Vol. 260). https://doi.org/10.1016/j.chemosphere.2020.127659

Thompson, J. T., Robey, N. M., Tolaymat, T. M., Bowden, J. A., Solo-Gabriele, H. M., & Townsend, T. G. (2023). Underestimation of Per- and Polyfluoroalkyl Substances in Biosolids: Precursor Transformation During Conventional Treatment. *Environmental Science and Technology*, *57*(9). https://doi.org/10.1021/acs.est.2c06189

Vu, C. T., & Wu, T. (2022). Recent progress in adsorptive removal of per- and poly-fluoroalkyl substances (PFAS) from water/wastewater. *Critical Reviews in Environmental Science and Technology*, *52*(1). https://doi.org/10.1080/10643389.2020.1816125

Wang, X., Guo, S., Huang, Q., Zhu, Y., & Zhang, Y. (2023). A novel biomass pyrogenic index and its application coupled with black carbon for improving polycyclic aromatic hydrocarbon source identification. *Environmental Monitoring and Assessment*, *195*(7). https://doi.org/10.1007/s10661-023-11494-1

Wang, X., Zhang, W., Lamichhane, S., Dou, F., & Ma, X. (2023). Effects of physicochemical properties and co-existing zinc agrochemicals on the uptake and phytotoxicity of PFOA and GenX in lettuce. *Environmental Science and Pollution Research*, *30*(15). https://doi.org/10.1007/s11356-023-25435-5

Wasfi, R., Moussa, H. A., Bakr, R. O., Abdeltawab, N. F., & Megahed, S. A. (2023). Anaerobic biodegradation of anthracene by oral Firmicutes isolates from smokers and its potential pathway. *International Biodeterioration and Biodegradation*, *180*. https://doi.org/10.1016/j.ibiod.2023.105598

Winchell, L. J., Wells, M. J. M., Ross, J. J., Fonoll, X., Norton, J. W., Kuplicki, S., Khan, M., & Bell, K. Y. (2021). Analyses of per- and polyfluoroalkyl substances (PFAS) through the urban water cycle: Toward achieving an integrated analytical workflow across aqueous, solid, and gaseous matrices in water and wastewater treatment. In *Science of the Total Environment* (Vol. 774). https://doi.org/10.1016/j.scitotenv.2021.145257

Yadav, S., Ibrar, I., Al-Juboori, R. A., Singh, L., Ganbat, N., Kazwini, T., Karbassiyazdi, E., Samal, A. K., Subbiah, S., & Altaee, A. (2022). Updated review on emerging technologies for PFAS contaminated water treatment. In *Chemical Engineering Research and Design* (Vol. 182). https://doi.org/10.1016/j.cherd.2022.04.009

Zhang, M., Zhao, X., Zhao, D., Soong, T. Y., & Tian, S. (2023). Poly- and Perfluoroalkyl Substances (PFAS) in Landfills: Occurrence, Transformation and Treatment. In *Waste Management* (Vol. 155). https://doi.org/10.1016/j.wasman.2022.10.028

Zhao, L., Cheng, Z., Zhu, H., Chen, H., Yao, Y., Baqar, M., Yu, H., Qiao, B., & Sun, H. (2023). Electronic-waste-associated pollution of per- and polyfluoroalkyl substances: Environmental occurrence and human exposure. *Journal of Hazardous Materials*, *451*. https://doi.org/10.1016/j.jhazmat.2023.131204

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