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Review

Industrial Applications, Environmental Fate, Human Exposure, and Health Effects of PFAS

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Abstract

Poly- and perfluoroalkyl substances (PFASs) are persistent environmental pollutants widely used in industrial applications due to their thermal stability and chemical resistance. However, their persistence in the environment and potential health risks, including developmental and immunological issues, have raised significant concerns. This review highlights the industrial uses, environmental fate, and bioaccumulation of PFASs, emphasizing their widespread presence in air, water, soil, and biota. Major sources of PFAS contamination include industrial discharges, wastewater treatment, and military sites. The atmospheric transport of PFASs contributes to their deposition in remote ecosystems, while aquatic and soil contamination stems from both point and nonpoint sources. Bioaccumulation studies reveal that PFASs accumulate in organisms, leading to potential human exposure through food, water, and consumer products. This review calls for further research to address knowledge gaps in PFAS detection, behavior, and health impacts, while advocating for improved regulations to limit their release and exposure.

Keywords: per- and polyfluoroalkyl substances; industrial importance; environmental fate; exposure pathways; health concerns

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1. Introduction

PFASs refer to numerous anthropogenic substances that have a fluorinated carbon chain with an aliphatic structure [1]. PFASs are a large class of synthetic "forever chemicals" characterized by carbon–fluorine bonds, which are among the strongest in organic chemistry, granting them extreme stability. A key distinction is made between perfluoroalkyl substances, where all hydrogen atoms on the carbon chain are replaced by fluorine, and polyfluoroalkyl substances, which still contain at least one carbon atom with hydrogen. These compounds are further classified by their chain length and functional groups, dictating their environmental behavior and persistence. The molecular structure of PFASs plays a significant role in determining their chemical and physical properties. Their highly fluorinated part makes them both hydrophobic and lipophobic, while the functional group allows them to interact with molecules that have polarity [2]. Gardiner [3] explains that PFASs are extensively utilized in industrial applications because of their distinctive chemical characteristics, such as excellent thermal stability, resistance to chemical breakdown, water and oil repellency, and low surface energy. Because of these characteristics, PFASs are well-suited for use in products like

non-stick cookware coatings, firefighting foam, water-repellent fabrics, and lubricants used in various industries. Without PFASs, many industries would face challenges in maintaining product durability, functionality, and efficiency. For example, firefighting foams would lose their effectiveness in suppressing high-intensity fires, non-stick cookware might degrade more quickly, and water-repellent materials could fail under harsh conditions, leading to increased costs and reduced performance in various sectors.

PFASs are valuable in industrial applications due to their resistance to degradation, but this very characteristic also raises concerns about their long-lasting presence in the environment. A large number of PFASs can build up in the bodies of humans and animals over time. Since 1999, the Centers for Disease Control and Prevention (CDC) has been monitoring PFASs (per- and polyfluoroalkyl substances) levels in the U.S. population as part of the National Health and Nutrition Examination Survey. The data has consistently shown that PFAS compounds, such as perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), and perfluorohexanesulfonic acid (PFHxS), are present in the blood of nearly 99% of individuals sampled. Exposure to these substances has been associated with negative health impacts, including developmental disruptions, immune system impairments, and adverse effects on the cardiovascular and liver systems [2].

Various efforts to cut down PFAS emissions, limit their production, and reduce their usage have caused some manufacturers to gradually stop making and using specific PFAS compounds, often replacing them with shorter-chain PFASs or fluorine-free alternatives like siloxanes and hydrocarbon polymers. For instance, polymers that had long perfluoro alkyl side chains containing more than seven fluorinated carbon atoms have been substituted with alternatives that have shorter chains, typically with four or six carbon atoms. Ongoing efforts are also focused on reducing the number of leachable substances in fluoropolymers and side-chain fluorinated polymers. These materials may contain unreacted monomers, small-chain oligomers, and other nonpolymeric PFASs that are introduced during the production process. Governments have implemented restrictions on certain PFASs, typically regulating them individually and allowing exemptions in specific cases. However, due to the durability of PFASs, their widespread presence, and continued use, humans and wildlife remain exposed [4,5].

Per- and polyfluoroalkyl substances (PFASs) have become a significant concern due to their widespread presence in various environmental and industrial products. Despite ongoing research [2,6,7], a clear understanding of the distribution and impact of PFASs in industrial products is still lacking. Over the last ten years, research on PFASs has grown rapidly, with many studies detecting these substances in the environment, as well as in humans and various animal species. Despite significant progress, there remain gaps in understanding the ways in which the production and environmental discharge of PFASs lead to their build-up in human and animal tissues. This issue was a central topic at the 2019 meeting of the Society of Environmental Toxicology and Chemistry (SETAC) on PFAS risk assessment.

Understanding the use of PFASs is crucial for assessing the risks they pose to humans and the environment. This article reviews information from the scientific literature, patents, and regulatory data, focusing on industrial applications, food packaging, medical uses, and pesticides. While patents provide insights into potential uses [6,8,9], they do not confirm implementation.

To our knowledge, this is the only review that comprehensively discusses various aspects of PFASs, including their industrial uses, environmental fate, human exposure, and associated health impacts. The scope of this review is to provide a detailed and up-to-date synthesis of the current state of knowledge regarding PFASs, focusing on both established and emerging applications of these substances. This review examines the industrial uses

of PFASs across multiple sectors, such as food packaging, medical products, firefighting foams, and pesticides; as well as textiles, electronics, and other consumer goods, shedding light on their widespread utility due to their unique chemical properties. It also assesses the environmental fate of PFASs, detailing their persistence, bioaccumulation, and potential for long-range transport, alongside the challenges involved in their detection and remediation. Furthermore, this review investigates human exposure to PFASs, identifying various pathways of contamination, including contaminated water, food, consumer products, occupational exposure, and indoor environments, while highlighting vulnerable populations and regions with higher exposure risks. Additionally, it evaluates the health impacts of PFASs by summarizing the latest toxicological studies and epidemiological evidence linking these substances to health outcomes such as cancer, developmental toxicity, immunological effects, and endocrine disruption. The objective of this review is to fill gaps in the literature and provide a comprehensive understanding of PFASs, integrating insights across industrial applications, environmental fate, exposure pathways, and health effects to guide both future research and policy decisions aimed at mitigating their risks.

2. Literature and Methodology

A literature search was conducted using keywords like "perfluor", "fluor", and related terms on the EPA's Desktop Library, Google Scholar, and Google Patents. References on PFAS use were reviewed, including manufacturer websites and Safety Data Sheets (SDS). Government databases like the EPA's "CompTox Chemicals Dashboard" were analyzed. Studies on PFAS contamination, transport, and health effects were reviewed, including works by Habib et al. [10] and Sun et al. [11]. A search for PFASs in soil used Web of Science, Google Scholar, and Google with terms like "PFAS", "Perfluor", "PFC", "soil", "water", and "air". References from identified studies were checked. Publications focusing only on precursor compounds were excluded. PFAS exposure routes include diet, water, air, dust, hand-to-mouth contact, and skin absorption. The search covered historical and emerging trends in PFAS contamination and exposure to understand their environmental and health impact.

3. Industrial Applications of PFASs

PFASs are widely used across numerous industries, categorized into 25 general groups, with many applications overlapping. For instance, PFAS-coated textiles are relevant to both the medical and textile industries. In this context, users are primarily described within the industry where the product is made or utilized, though references to other relevant sectors are also briefly mentioned. An expanded literature search provided additional references and insights into previously reported uses of PFASs. However, trade secrets and the absence of disclosure requirements hinder complete transparency regarding specific applications. Patents have proven valuable in revealing previously undisclosed uses of PFASs. Although the PFAS concentration in products is not always provided, it is occasionally noted in some cases. A study by Glüge et al. [6] identified 200 applications across 64 use categories, demonstrating the extensive presence of fluorochemicals in industrial and everyday life.

3.1. Consumer and Personal Care Industries

Due to their surfactant properties, PFASs are widely used in consumer goods to provide water, stain, and oil resistance, as well as to enhance product performance in cleaning and personal care items. A major historical use is in the textile and packaging industries, where they impart durable water and grease repellency to products like outdoor apparel, carpets, and food-contact paper [12]. While long-chain PFASs are dominant, regulatory actions, such as those by the U.S. FDA [13], are driving a shift toward short-chain alternatives.

In cleaning and maintenance products, PFASs are valued for their ability to reduce surface tension. They are incorporated into household detergents to minimize streaks on glass, in windshield washer fluids to prevent icing, and in specialized industrial cleaners for tasks like descaling membranes [14]. Some formulations, such as certain electronics cleaners, can contain very high PFAS concentrations by weight [15,16]. Furthermore, PFASs are key components in lubricants like PTFE (Teflon™) to reduce friction [17].

Within the cosmetics and personal care industry, PFASs function as emulsifiers, lubricants, and oil-repellent agents. This enhances the texture and performance of products including sunscreens, hair conditioners, and hand sanitizers [18]. Their application also extends to dental care, where they provide antibacterial benefits [19].

3.2. Chemical and Material Processing Industries

PFASs are critical in chemical processing and material science, primarily for creating advanced materials and protective coatings. A key application is in material synthesis, where supercritical fluids containing PFASs are used to produce stabilized metal nanoparticles and fine ceramic powders with controlled nanostructures [20–22].

Their most widespread industrial use is in coatings, where they impart durable, protective properties. PFAS-enhanced coatings provide oil- and water-repellency, antifouling, and corrosion resistance to substrates like metals, stone, and construction materials [23,24]. Notable examples include PTFE (Teflon™) and PVDF coatings, which protect surfaces from environmental wear. These properties also benefit specialized applications, such as anti-mist films for greenhouses [14] and low-refractive-index resins for optical components [25].

Furthermore, PFASs function as high-performance additives in formulations. In inks, they act as surfactants and grinding aids, improving pigment dispersion and image quality in inkjet printing. They are also used as lubricants in products like industrial coatings and ski waxes to reduce friction and wear [26].

3.3. Plastics, Resins, and Rubber

PFASs are crucial for manufacturing high-performance fluoropolymers and elastomers, materials prized for their exceptional chemical resistance and thermal stability. These applications range from structural materials like PTFE and ETFE, used in medical devices and as a glass substitute, to specialized components such as Nafion membranes for electrochemical systems and perfluoroelastomers for seals in extreme environments [22,27,28]. Furthermore, PFASs act as processing aids and additives, for instance as flame retardants in plastics [24]. A critical consideration is that the industrial fluorination process, while not directly using non-polymer PFASs, can lead to their formation as persistent and unintended byproducts [29].

3.4. Recycling and Material Recovery

PFASs (per- and polyfluoroalkyl substances) play an essential role in metal recovery, particularly rare earth metals, through solvent extraction processes. Studies have demonstrated that PFASs can achieve nearly 100% recovery in just two extraction steps, with the solvent being reusable [30]. They are employed to extract metals such as palladium from electronic waste [31] and indium from liquid crystal displays. Additionally, PFASs have been tested for recovering platinum group metals from wastewater in plating operations [30–32].

Supercritical carbon dioxide, when combined with PFAS surfactants, has demonstrated effectiveness in extracting cesium which is radioactive, from contaminated soil, achieving high extraction efficiencies from sediment [33,34]. Additionally, PFASs have the ability to extract both radioactive and non-radioactive metals from solid and liquid phase [35,36]. They have also been employed in the regeneration and recovery of solvents, such as n-hexane, from waste gases [37].

3.5. Pesticides and Fertilizers

PFASs have been incorporated into pesticides as both active and inactive ingredients, depending on regulatory standards. While active ingredients are responsible for pest control, inactive ingredients assist in stability and delivery. A review of the EPA's pesticide database has identified several PFAS compounds listed as both active and inactive ingredients [38]. Although PFASs have been phased out as active ingredients in American's pesticides, they continue to function as inert surfactants, aiding in the penetration and wetting of surfaces in formulations, especially herbicides and insecticides. PFASs also act as foam-breaking agents in pesticide mixtures to ensure proper surface wetting.

PFAS derivatives are commonly used in insecticides and fungicides to increase mixture stability and improve application effectiveness [39]. FTOH-based phosphates were previously authorized as inert ingredients in pesticides, but the U.S. EPA revoked this approval in 2006 [40]. In fertilizers, PFASs serve as coatings to reduce dust and improve handling. Patents have cited PFAS polymers as coating ingredients to minimize environmental contamination during fertilizer application [41].

3.6. High-Tech Industrial Applications

PFASs play a critical and versatile role in electronics and energy storage due to their unique chemical stability and surfactant properties. In semiconductor manufacturing, they are essential for photolithography, where they lower the surface tension of etching solutions to enable the precise production of miniaturized components [9,14]. Their dielectric and thermal properties are exploited in fluoropolymer coatings that insulate wires and protect circuit boards, as well as in specialized cooling fluids like 3M's Fluorinert for data centers [42]. A major application is in energy technologies, where PFASs are foundational in lithium-ion batteries and PVDF is widely used as a binder and separator [43], and in fuel cells, where perfluorinated ionomer membranes like Nafion are critical for ion conduction [21,44]. From soldering and cleaning to advanced battery and semiconductor fabrication, PFASs are integral to the functionality and performance of modern electronic systems.

3.7. Medical Uses

PFAS-based emulsions were first explored in 1966 by Clark and Gollan, who investigated their use as blood substitutes due to their oxygen-carrying properties [45]. These emulsions have also been studied for treating decompression illness [46] and as potential treatments for respiratory failure [47]. Several patents describe PFAS-based emulsions for drug delivery or blood substitute applications [48–50].

Among the PFAS-based injectable oxygen carriers, Fluosol was the first to be administered to humans in 1978. Although it showed promise for treatments such as oxygen delivery during coronary angioplasty, its production ceased in 1994 due to other harmful outcomes [51]. Perftoran, a therapeutic product based on PFASs, has been used in several countries including Russia, Ukraine, Kazakhstan, and Mexico. In the United States, it is known by the brand name Vidaphor, although it is still pending clinical experiments [52]. PFAS emulsions have been extensively studied for enhancing tumor oxygenation to improve the outcomes of radiation therapy, chemotherapy, and other treatments [52].

PFASs also play an important role in medical imaging and diagnostics, serving as contrast agents for MRI, ultrasound, PET, and multimodal imaging [52]. Some PFASs are incorporated into radiotracers for molecular PET imaging due to their compatibility with fluorine-18 (18F) [53]. Perfluorocarbons have also been utilized in the development of nanoparticles, which are applied in magnetic resonance imaging (MRI) [50] and treatment with drug, particularly for cancer and cardiovascular treatments. PFASs are integral to drug-delivery microspheres and as components in metal complexes for radiodiagnosis [54].

In ophthalmology, PFASs are mixed with silicone oils to treat retinal detachment, improving reattachment rates [55]. Other patents highlight PFAS use in nerve regeneration and pharmaceutical compositions for CNS and PNS injury treatments. PFASs are also used in pharmaceutical manufacturing as foam dampening agents [56].

Fluorinated compounds are common in pharmaceuticals, either as a single fluorine atom or a trifluoromethyl group [53]. A comparison between FDA-approved drugs and the EPA's PFAS structure database identified seven overlapping compounds [57]. PFASs are widely used in medical device manufacturing, including coatings for surgical tools and medical devices for properties such as thermal stability and hydrophobicity [58]. Fluorinated polymers in contact lenses enhance oxygen permeability and resist deposits [59,60]. PFASs are also crucial in medical textiles, such as surgical coverings and gowns, which are treated with fluorinated compounds for enhanced resistance to water and oils [24].

3.8. Metal Coating and Surface Finishing

The utilization of PFASs has been extensively observed in metal plating and finishing processes, particularly in chrome plating. Historically, PFAS-based compounds have served as surfactants, wetting agents, and mist suppressants. Early PFAS formulations incorporated amino-functionalized PFASs, and by the late 1980s and early 1990s, sulfonate-based PFASs were introduced as second- and third-generation wetting agents and fume suppressants [9]. PFAS-based fume suppressants, like those containing organic fluorosurfactants with PFOS as the active component, are used in industrial processes [22,61].

In addition to their use in chrome plating, PFASs have been employed in other metal electroplating processes, including copper, nickel, and tin electroplating, where they act as leveling agents. These agents improve the quality of the plating and prevent defects such as drying cracks [14]. PFASs also enhance the properties of aluminum foil by treating it with compounds like Monofloroalkyl [14]. These substances improve electroplating bath stability and protect against corrosion and mechanical wear. Furthermore, PFAS-based dispersion products have been used to coat metals, contributing to the suppression of acid mists in electroplating operations.

PFAS contamination in wastewater from metal plating facilities has been reported, with studies from the U.S. EPA and Michigan Department of Environment confirming detectable levels of PFASs in wastewater samples from chrome plating operations [62].

3.9. Mining Industry

In the mining industry, PFASs are commonly employed to optimize the extraction and recovery of valuable metals such as copper and gold. One of the ways they achieve this is through the use of fluoroaliphatic surfactants, which play a critical role in improving the efficiency of leaching processes to extract precious metals from ores. These surfactants are also utilized in the flotation process, a technique that aids in separating metal salts from the surrounding soil, thus enhancing the overall metal extraction process [14]. Additionally, PFASs have been applied in electrowinning and ore flotation operations, which are critical for the recovery of minerals in the mining process. These compounds also serve as mist suppressants in mining operations to improve air quality.

PFAS-based chemicals are further explored in research for their role in the extraction of uranium from seawater and for improving the efficiency of various mining processes [63]. In the U.S., the EPA's proposed Significant New Use Rules (SNURs) outline specific PFAS applications for mining, including surfactants for enhanced metal recovery.

3.10. Oil and Gas Industry

The oil and gas industry has leveraged the properties of PFASs in several applications related to well stimulation, drilling, and oil recovery operations. PFAS compounds function

as Surfactants are used to reduce the surface tension, improving the ability of liquids to interact with and spread across surfaces, stabilize foam, and optimize wetting, thereby improving the efficiency of oil extraction. Fluorinated liquids have been incorporated into drilling and completion fluids, as well as in the creation of proppants for hydraulic fracturing. Notably, DuPont's Capstone fluorosurfactants and 3M's additives are widely used in these applications [9,14,64].

PFAS-based products have been found to improve the carrying capabilities of foam solutions and facilitate particle lifting in gas well stimulation. Furthermore, these substances are used to reduce evaporation losses in petroleum storage tanks and to form barriers that help contain and manage oil spills [14]. Research has also proposed the use of PFAS-treated materials such as perlite or vermiculite to contain oil slicks, highlighting their role in spill containment efforts.

3.11. Safety and Defense Applications

PFASs have been integral to the development of energetic materials, such as explosives, propellants, and ammunition. The use of PFASs in pyrotechnic oxidizers dates to the mid-20th century, with fluoropolymers such as PTFE being combined with metals like magnesium and aluminum to create compositions that are useful in tracking flares and rocket propellants [65]. Fluoropolymers such as Viton-A, PCTFE, and Teflon are commonly used as binders in plastic-bonded explosives, offering improved mechanical properties and thermal stability. Other examples include polychlorotrifluoroethylene (PCTFE), which provides excellent chemical resistance, and polytetrafluoroethylene (PTFE), which enhances the durability and heat resistance of explosive formulations.

PFAS compounds are also vital in fire-fighting applications, particularly in aqueous film-forming foams (AFFF). These foams were first developed in the 1960s and have been used extensively by military forces, airports, and fire departments to combat hydrocarbon fires [66]. Initially, AFFF formulations used perfluorinated carboxylic acids, which were later replaced by PFOS-based AFFFs in the 1970s and fluorotelomer-based AFFFs by 1975. These foams remain essential for modern fire-fighting operations, with updates to AFFF specifications introduced by the U.S. Department of Defense in 2017 to limit the presence of PFOA and PFOS to 800 ppb in concentrates [25].

3.12. Applications in Consumer Products and Surface Modifications

PFASs serve critical functions in a diverse range of consumer and industrial applications due to their unique surfactant and stability properties. In consumer sectors, they are used as fluorinated surfactants in dry cleaning to replace traditional solvents and as refrigerants in air conditioning systems. Industrially, they enhance the performance of adhesives and coatings, improving bond strength in materials like wood particleboard and providing durability for automotive and label applications [8,67]. In essence, the utility of PFASs spans over 200 use categories from textiles and cosmetics to electronics and oil extraction primarily leveraging their oil and water repellency, thermal stability, and ability to reduce surface tension. However, this very pervasiveness, coupled with their environmental persistence, underscores the critical need to understand their environmental fate and long-term impact.

The most common industrial applications of surface-active agents include consumer goods and personal care, where they aid in surface tension reduction and water resistance, and the textile industry, which focuses on water, oil, and stain resistance (Table 1). The chemical and material processing sector uses them for properties like wetting, anti-fouling, and gloss enhancement. The plastic, resin, and rubber industries leverage these agents for chemical resistance and flame retardance, while oil and gas applications use them for foam stabilization and oil extraction. The medical industry benefits from biocompatibility and drug delivery properties. However, industries like pesticides and fertilizers and recycling are most pollutive due to chemical waste and environmental contamination from metal recovery.

Table 1. Overview of PFAS applications across industries.

Industry Sector	Typical Product Types	Main Functional Roles	Citations
Consumer Goods & Personal Care	Household cleaning agents, detergents, windshield washer fluids, fabric care products, cosmetics	Surface tension reduction, wetting, antifogging, stain and water resistance, lubricants	[14,17,56]
Textile Industry	Protective clothing, carpets, outdoor fabrics, food-contact packaging	Water, oil, and stain resistance, durability, cleanliness, grease resistance in packaging	[13,25]
Chemical & Material Processing	Ceramics, metal nanoparticles, coatings, inks	Surface tension, wetting, penetration, antifouling, antistatic properties, metal recovery, gloss enhancement	[20,23,25,67]
Plastics, Resins & Rubber	Fluoropolymers, medical devices, electrochemical applications	Chemical resistance, flame resistance, low permeability, high-temperature stability, processing aids	[24,27,43]
Recycling & Material Recovery	Metal extraction, solvent recovery	Metal recovery (e.g., palladium, platinum), extraction from contaminated soil, solvent regeneration	[30,31,33,34]
Pesticides & Fertilizers	Herbicides, insecticides, fungicides, fertilizers	Wetting agents, foam-breaking, stability, dust reduction	[38–41]
High-tech Industrial Applications	Electronic components, semiconductor manufacturing, cooling systems	Surface tension reduction, stability in electronic components, corrosion protection, improved processing	[14,25,42,44]
Medical Uses	Blood substitutes, drug delivery, imaging agents, medical devices	Oxygen-carrying properties, biocompatibility, stability, imaging, drug delivery, surface hydrophobicity	[45,51,53,58,59]
Metal Coating & Surface Finishing	Chrome plating, copper, nickel, tin electroplating, aluminum foil	Surface tension reduction, leveling, mist suppression, corrosion protection, wear resistance	[14,61,62]
Mining Industry	Metal extraction, flotation agents, electrowinning	Enhanced metal recovery, mist suppression, efficiency in leaching processes	[14,36,63]
Oil & Gas Industry	Drilling fluids, completion fluids, proppants, foam stabilization	Surface tension reduction, foam stabilization, improved oil extraction, oil spill containment	[9,14,64]
Safety & Defense Applications	Firefighting foams (AFFF), explosives, propellants, ammunition	Flame retardants, fire suppression, explosive binders, pyrotechnic applications	[23,65,66]
Consumer Products & Surface Modifications	Dry cleaning products, refrigeration, adhesives, coatings	Fabric protection, faster drying, low boiling points, enhanced adhesion and durability in coatings	[8,67]

4. Environmental Fate and Transport of PFASs

4.1. Persistence and Mobility Characteristics

PFASs are a class of chemicals known for their exceptional chemical stability and persistence in the environment. Their unique properties arise primarily from their strong carbon–fluorine (C–F) bonds, which are reinforced by the overlap between fluorine's 2s and 2p orbitals with the carbon orbitals [68]. As the number of fluorine atoms attached to the central carbon increases, the strength of these C–F bonds is enhanced. The fluorine atoms serve as both steric and electrostatic shields, providing resistance to nucleophilic attacks on the central carbon [69]. Additionally, the high electronegativity of fluorine in C–F bonds increases the polarization of the molecules, making PFAS compounds more ionic, with stronger bonds and greater acidity compared to their hydrocarbon counterparts [70,71].

The environmental behavior of PFASs is strongly influenced by their solubility and volatility. The Henry's Law constant (Kaw) determines the partitioning between air and water, affecting the volatility of these compounds [72,73]. Neutral PFAS compounds generally exhibit higher Kaw values, leading to greater volatility [74]. Furthermore, the solubility of PFASs affects their mobility in the environment, with shorter-chain PFASs (e.g., C4 PFBA and C4 PFSA) being more soluble than longer-chain counterparts, result-

ing in increased environmental mobility [75,76]. Fluorotelomers, such as FTOH, tend to have higher volatility compared to longer-chain perfluorinated compounds like PFOA (Supplementary Table S1) [77]. The solubility of PFASs is also affected by structural characteristics, pH, salinity, and the presence of organic matter, contributing to their persistence in both aqueous and gaseous phases [78,79].

PFAS compounds exhibit amphiphilic properties, with both hydrophobic fluorocarbon chains and hydrophilic functional groups, which contribute to their remarkable ability to reduce the surface tension of water [80]. This characteristic enhances their mobility and interaction with biological membranes, as well as their sorption to soil particles. The surface tension of PFASs is influenced by factors such as chain length, pH, and electrolyte composition [81]. Longer-chain PFASs display significantly lower critical micelle concentrations (CMC), which are dependent on both the hydrophobic chain length and counterions [82].

Another important property of PFASs is their bioaccumulation potential. These compounds exhibit strong proteinophilicity, meaning they tend to bind to proteins, especially in the bloodstream, enhancing their stability and solubility, and leading to their accumulation in various organs, including the heart and kidneys [83]. This bioaccumulation is a significant concern as it prevents easy metabolism or excretion, resulting in long-term accumulation, particularly for long-chain PFAAs, which are more likely to bioaccumulate than shorter-chain compounds [84]. In aquatic environments, PFASs can bind to proteins in water and sediment, increasing their bioavailability and leading to bioaccumulation in aquatic organisms. This bioaccumulation is particularly concerning for higher trophic levels, with PFAS concentrations escalating in top predators, including polar bears and humans [85].

The environmental behavior of PFASs is also influenced by their dissociation constant (pKa). Studies indicate that for perfluorinated alkanonic acids, the pKa decreases for compounds with one to three carbon atoms and increases for those with five carbon atoms. The pKa values of PFASs, such as PFOA, range from -0.2 to 3.8, affecting their ionization at different pH levels and influencing their mobility and behavior in soil environments [86]. The dissociation constant impacts the ionization and solubility of PFASs, further affecting their interaction with environmental systems.

Additionally, the soil-water partition coefficient (K_d) plays a critical role in understanding how PFASs interact with soil and water. Longer-chain PFAS compounds typically exhibit higher sorption affinities for soil, influenced by hydrophobic interactions and the molecular size of the compounds [87,88]. The pH of the soil is also crucial, as more acidic conditions tend to increase the sorption coefficient (K_d) for anionic PFASs. Surface complexation with uncharged organic and mineral soil surfaces further influences their behavior [75,87]. Based on the sorption characteristics of different PFAS compounds, the following order is observed: zwitterions > sulfonamides > telomers > PFSAs > PFCAs > ethers.

The environmental persistence and transport of PFASs are further complicated by the interplay between their pKa and K_d values. Because most PFASs are strong acids and remain ionized in the environment, their high solubility would typically suggest low soil retention. However, sorption is significantly enhanced by factors beyond simple hydrophobicity. For instance, the exceptional sorption strength of zwitterionic PFASs is attributed to electrostatic attractions, where both positive and negative charges on the molecule bind to soil particles. This explains their position at the top of the sorption hierarchy, making them less mobile but highly persistent at contamination sites.

Furthermore, the influence of soil pH creates a critical dynamic. In acidic soils, the increased sorption of anionic PFASs occurs because a lower pH reduces the negative charge on soil organic matter and mineral surfaces, decreasing electrostatic repulsion and allowing for stronger hydrophobic and complexation interactions. This pH-dependent behavior

means that PFAS mobility can vary dramatically across different landscapes. Consequently, ether-based PFASs and short-chain PFCAs, which sit at the bottom of the sorption order, pose a greater risk for long-range transport, as they are less affected by these sorption mechanisms and can readily migrate through soil to contaminate groundwater.

The persistence and environmental distribution of PFASs are influenced by their chemical stability, solubility, volatility, amphiphilic properties, and bioaccumulation potential. Their strong C–F bonds provide stability and resistance to degradation, while their ability to interact with biological systems complicates efforts to mitigate their environmental and health impacts.

4.2. Atmospheric Transport and Deposition

Fluoropolymer manufacturing plants, wastewater treatment plants [10,11], landfills, and military bases [89,90] are major sources of PFAS pollution in the environment. From 1951 to 2015, about 2612 tons to 21,500 tons of PFCAs were discharged worldwide, with emissions increasing over time, especially in Asia [91,92]. Some PFASs enter the environment directly through products like fire-extinguishing foam or ski wax [93]. Airborne emissions of PFASs have been associated with contamination of well water in regions located downwind of significant sources. This connection highlights the potential for PFASs to spread through atmospheric processes and affect local water supplies [76,94]. PFASs inside buildings can also escape into the outdoor air through open doors, windows, or leaks in the structure. Once in the air, PFAAs, which break down very slowly, can travel far and settle into water and soil through wet and dry deposition [1,95].

PFASs are carried through the atmosphere in both gas and particle forms, enabling their transport over long distances from their initial sources [96,97]. This atmospheric movement allows for the deposition of these chemicals in distant and remote locations, far from their original points of release, raising concerns about their widespread environmental impact [98–100]. Volatile PFAS precursors, such as FTOHs, are primarily found in the gaseous state and can persist in the atmosphere for up to 80 days, enabling long-range transport [94]. Once oxidized, these precursors contribute to the formation of persistent PFAAs, which act as secondary sources of PFAS deposition [101]. Neutral PFAAs can exist in the gas phase, while ionized PFAAs may attach to aqueous aerosols. However, the extended atmospheric transport of perfluoroalkyl acids (PFAAs) remains poorly understood, with limited research on how these compounds travel across vast distances and their potential impacts on remote ecosystems [102,103]. Despite evidence of their widespread presence in regions far from known sources, the specific mechanisms of their atmospheric movement and deposition are still not fully characterized, highlighting the need for further investigation into their global distribution and environmental persistence.

The way PFASs interact with aerosols is influenced by the physical and chemical properties of the particles, which can vary greatly depending on their composition and environmental factors. Aerosols are tiny particles suspended in the air and consist of organic, inorganic, and aqueous components [104]. They can be categorized into primary aerosols, which are directly released into the atmosphere through natural or human activities, such as sea spray, pollen, or ash, and secondary aerosols, which form through chemical reactions within the atmosphere [100]. The behavior of aerosols, including how they mix or separate, is largely dependent on their composition and the surrounding humidity levels, with some aerosols being homogeneously mixed while others may undergo phase separation, potentially affecting their ability to interact with pollutants like PFASs [105]. Short-chain, water-soluble PFASs tend to partition into the bulk of aqueous aerosols, where they are more easily incorporated into the liquid phase, while longer-chain PFASs are more likely to stay on the surface of the particles due to their larger molecular size and hydrophobic

nature. Additionally, PFASs with lower vapor pressures have a higher tendency to adhere to particulate matter, as they are less volatile and are more efficiently transported through the atmosphere when attached to these particles [100].

The Intergovernmental Panel on Climate Change (IPCC) recognizes aerosol–cloud interactions as a major source of uncertainty in predicting radiative forcing, which affects the energy balance of the atmosphere. These interactions, which influence cloud formation and properties, are difficult to quantify accurately in climate models, making it challenging to fully understand their impact on climate systems [100]. Aerosols can either scatter sunlight, causing cooling, or absorb sunlight, contributing to warming [106,107]. Hygroscopic aerosols can act as cloud condensation nuclei (CCN) by absorbing water [47]. PFASs on aerosol surfaces lower surface tension, while PFASs in the bulk reduce vapor pressure, both affecting CCN activity. Aerosols with surfaces suitable for ice nucleation may also form ice clouds, and PFASs could enhance this process [108]. However, the role of PFASs in cloud formation remains understudied.

In indoor environments, PFAS dynamics differ due to the higher between surface and volume ratio. Volatile organic compounds (VOCs), which remain in the gas phase outdoors [109–111], often interact with indoor surfaces [112]. While research on the role of surfaces and PM2.5 composition in VOC and SVOC partitioning is increasing, little is known about the behavior of ionic PFASs indoors. The characteristics of indoor aerosols and the environment are likely to influence the mass balance of ionic PFASs [113].

However, field studies on PFASs in the air remain limited, especially for PFAAs [114,115] and highly volatile, short-chain PFAS precursors such as 4:2 FTOH, partly because conventional air samplers cannot easily capture these compounds.

Based on the data (Table 2), PFAS contamination exhibits significant variability, with the most severe concentrations observed in Europe and Oceania. Europe reports an extreme maximum PFOS concentration of 8600 ng/g in agricultural areas, while Oceania records high levels of 1388 ng/g PFOA and 1692 ng/g PFOS due to contaminated irrigation practices. In North America and industrial regions of China, PFAS levels are moderate to high, with the United States reaching 12 ng/g PFOS and Chinese sites reporting up to 5500 ng/g of total PFASs. In stark contrast, South Korea's coastal areas remain relatively unaffected, with maximum concentrations of only 3.4 ng/g PFOA and 1.7 ng/g PFOS. These trends underscore that industrial activities and certain agricultural practices are the primary contributors to elevated PFAS contamination globally.

Table 2. Worldwide PFAS contamination in environmental sites with concentration values across different regions.

Region	Country/Area	Investigated Sites	PFAS Concentration (ng/g)	Max. PFOA/ PFOS (ng/g)	Comments	References
Asia	South Korea	Estuarine/ coastal areas	0.3–3.9	3.4/1.7	Lower PFAS levels in coastal areas.	[116,117]
	China (Tianjin, Wuhan)	Rivers/ Manufacturing plant	0.2–5500	0.5/2.4	Moderate to high contamination near industrial sites.	[118]
North America	USA (Minnesota, Ohio)	Home gardens/ Fluoropolymer industry	1.3–490	3.0/12	PFASs detected in agriculture, linked to industrial activities.	[119,120]
Europe	Sweden, Germany, France	Forests/ Agricultural areas	0.4–9250	0.6/8600	Forests less impacted, agriculture at risk.	[121]
Oceania	Australia	Irrigated agriculture	4.0–3067	1388/1692	Irrigation with contaminated water spreads PFASs.	[122]

4.3. Aquatic Ecosystems Contamination

According to Paul et al. [123] and Prevedouros et al. [64], over 95% of PFAS emissions are discharged into aquatic environments, with less than 5% released into the atmosphere.

PFASs enter aquatic ecosystems both from point sources, such as industrial wastewater, and from nonpoint sources, like runoff from contaminated areas. The total discharge of PFASs varies significantly, ranging from 10 g per day [124] to 10,000 g per day mol [125], depending on water usage and the capacity of sewage treatment plants. PFAS precursors can degrade into PFCAs and PFSAs, increasing their concentrations in receiving water bodies [126]. As PFAS precursors degrade and older products, still in use or discarded, continue to release long-chain PFASs, these substances are expected to keep entering water systems. These substances can also leach back into water from soil, sediments, and ice [115]. Additionally, emissions of short-chain PFASs and their precursors are increasing.

The key implications for groundwater and environmental risk from PFASs are multifaceted. Firstly, there is widespread and persistent contamination, as PFASs are detected in groundwater worldwide, often exceeding drinking water guidelines, with both legacy and emerging compounds present even in remote or rural areas [127,128]. This is exacerbated by multiple sources and the high mobility of PFASs; major sources include industrial discharges, firefighting foams, landfills, and wastewater, which lead to off-site migration and long-term contamination of both groundwater and connected surface waters [129,130]. These issues are critical due to the significant health and ecological concerns associated with PFAS, as PFAS exposure is linked to adverse health effects—such as immune, developmental, and metabolic toxicity—and ecosystem risks, especially since many compounds are bioaccumulative and toxic [127,130]. Finally, there are considerable regulatory and monitoring challenges, as current monitoring may underestimate the true PFAS burden due to limited analyte coverage and evolving definitions, highlighting a need for improved detection, broader regulation, and advanced water treatment technologies [127,129].

Volatile PFASs released into the air can degrade or form intermediates during atmospheric oxidation (Figure 1). These intermediates may eventually transform into more stable PFAS compounds, like PFCAs and PFSAs, which ultimately settle in aquatic environments [10]. Nonpoint sources, such as runoff from contaminated soils and streets due to biosolid applications, as well as wet and dry atmospheric deposition, contribute significantly to PFAS pollution [131]. Both point and nonpoint sources contribute to the exposure of aquatic ecosystems to complex mixtures of PFASs, which reflect the various environmental characteristics and extensive uses of these substances. Pan et al. [132] conducted a study examining the concentrations of PFCA and PFSA in 160 surface water samples collected from countries such as South Korea, Germany, Sweden, the Netherlands, the United Kingdom, China, and the United States. The results indicated that various PFAS compounds were consistently detected across these regions, highlighting their global presence in surface waters. In another study, Kaboré et al. [133] analyzed 133 different PFASs in drinking water samples. They found that the levels of PFOS and PFOA were below the U.S. EPA's health advisory limit of 70 parts per trillion (ppt), with concentrations ranging from less than 5 ppt to 439 ppt, emphasizing the widespread presence of PFASs in drinking water. In the Arctic Ocean, Yeung and colleagues detected 13 PFAS compounds in concentrations ranging from 5 to 343 picograms per liter (pg/L), showing that PFASs have reached even the most remote and pristine environments [134]. These studies collectively emphasize the global persistence and widespread contamination of aquatic and oceanic ecosystems by PFASs.

Table 3 highlights a significant global disparity in PFAS water contamination, with extreme concentrations associated with specific industrial point sources. Notably, Canadian creeks exhibit an alarming 80,000 pg/L of PFOS, while Germany's Rhine River reports a concerning 519 ng/L of PFOS. In stark contrast, Afghanistan shows negligible PFOS levels of less than 0.03 ng/L. Many regions, including the USA, Australia, and France, display moderate but concerning PFOS and PFOA concentrations in drinking water, reinforcing the idea that industrial discharge is the primary cause of severe contamination. The data further

illustrates that PFAS contamination is a widespread issue, with lower-level detections in tap water across diverse countries, from China to Ghana, indicating a global challenge impacting water supplies regardless of a nation's level of development.

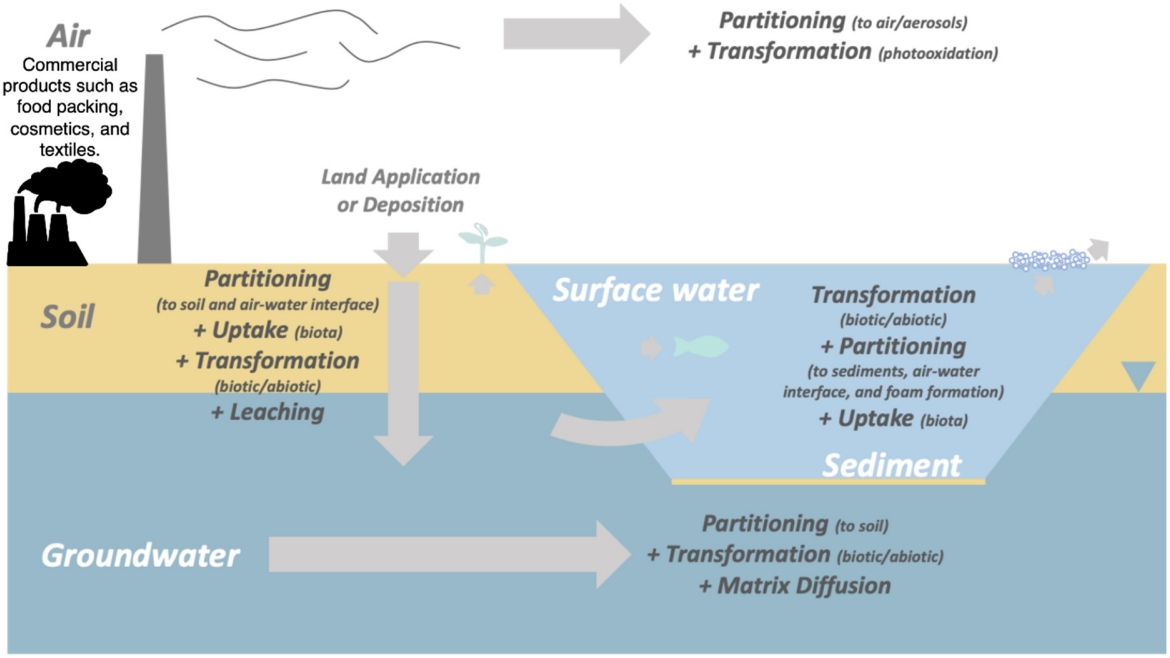

Figure 1. PFAS emission sources and partitioning across air, water, and soil.

Table 3. Global occurrence of PFAS contamination in water sources with concentration values across multiple regions.

Region/ Country	Location	Sampling Type	PFOS (Unit)	PFOA (Unit)	Other Notable PFASs	Study
USA	Mid-Ohio Valley (West Virginia)	Drinking water from 6 water districts and private wells	3.55 ng/mL	1.5–7.2 ng/mL	-	[135,136]
Canada	Toronto, Ontario	Water samples from creeks and rivers	80,000 pg/L	19,000 pg/L	PFNA, PFDA, PFUnA	[137]
Germany	Rhine River, Moehne River, Ruhr catchment area	River and drinking water samples	519 ng/L	-	PFHpA PFHxA	[138]
France	Various locations in France	Raw and treated water samples (331 raw, 110 treated)	22 ng/L	12 ng/L	PFBA, PFBS, PFHxA, PFPeA, PFHpA, PFNA, PFDA (detected in raw water)	[139]
Australia	34 locations across Australia	Drinking water samples	16 ng/L	9.7 ng/L	PFHxS	[140]
Japan	Osaka	Water samples from water purification plants	1.3–3.7 ng/L	6.5–48 ng/L	-	[141]
South Korea (Seoul)	Seoul Metropolitan area	Drinking water, human serum, and food samples	0.370–10.8 ng/L	<3.29 ng/L	PFNA, PFDA, PFCAs, PFSAs	[142]
China (Eastern China)	Eastern China (9 rivers, 9 lakes, 17 cities)	Tap water and surface water samples from rivers and lakes	1.4–175 ng/L	115–151 ng/L (Hangzhou exceeded USEPA standard)	PFHxS, PFHpA, others	[143]
India (Ganges River)	Along the Ganges River	Drinking water samples	0.8–4.9 ng/L	0.5–3.5 ng/L	PFHxA, PFHpA, PFPA	[144]
Afghanistan	Kabul and Ningarhar	Tap and well water samples	<0.03 ng/L	<0.015 ng/L	-	[145]
Ghana	Rivers of Kakum and Pra	Rivers and tap water samples	197–398 ng/L	197–200 ng/L	PFHxA, PFDA, PFPeA	[146]

4.4. Soil Contamination and Mobility

This section explains how PFASs interact in soil and with other parts of the environment, like air, water, and plants. It shows that PFASs from the air and groundwater are important sources of contamination in the soil. This section also looks at the factors that affect how PFASs move between water and the soil. Understanding these factors helps us to explain how PFASs accumulate in different environmental media.

PFASs are transported from the air to the soil via two processes: dry deposition and wet deposition. Dry deposition happens when particles in the air, which carry ionic PFASs (i-PFASs), settle onto surfaces like soil, plants, or water. The distribution of these particles in the atmosphere depends on their size, with smaller particles spreading more widely [147]. Once deposited, PFASs can be absorbed by plants, surface water, and soil, integrating into the environment [148]. Wet depositions occur when PFASs are carried by rain or snow, effectively washing them out of the air and depositing them onto the ground. This process has been observed globally, including in North America and Asia, making wet deposition a major pathway for PFASs to enter the soil [149,150].

PFASs can also form on snow or ice surfaces through the breakdown of precursors like FTOH when exposed to sunlight. This photochemical degradation increases the levels of i-PFASs in the soil after deposition [151,152]. The breakdown process is driven by reactions with OH radicals, which are highly reactive molecules [153]. Although wet deposition is the main route for PFASs to move from the air to the soil, long-chain PFASs can also bind to microplastics. These microplastics, though rarely, can be lifted by the wind and transported, adding another route for PFASs to reach the soil [154]. Overall, soil acts as a key to sink for airborne PFASs because it accumulates these compounds through various deposition pathways.

PFAS contamination in the soil occurs mainly through two routes: secondary and primary point sources. Primary sources include direct releases, such as the use of aqueous film-forming foams (AFFFs) during firefighting training exercises in designated areas (FFTAs), along with leaks or spills during the storage, handling, or cleaning of these foams [155]. Other primary sources involve direct discharges from industries that produce or use fluorinated chemicals [156] and landfill leachate seepage. Landfills often contain PFAS-rich waste such as municipal solid waste (e.g., stain-resistant products), sewage sludge, and industrial materials [89]. Secondary point sources are more widespread and include practices like applying fertilizers (e.g., wastewater sludge or compost) and irrigating agricultural areas with recycled wastewater [157]. Soils near primary sources, such as fluorochemical manufacturing facilities, are at higher risk of PFAS contamination, leading to indirect exposure through secondary pathways [157,158].

PFASs interact with soil based on their chemical properties, such as carbon chains length and their reactive groups. For example, long-chain PFAAs, such as PFOA, tend to form large clusters on kaolinite clay surfaces due to hydrophobic interactions and direct binding between the PFAA molecules and surface hydroxyl groups [159]. In contrast, short-chain PFAAs, like PFBS, do not form aggregates but still experience limited movement because their terminal functional groups (e.g., COO^-/SO_3^-) interact directly with soil hydroxyl groups, particularly in soils rich in kaolinite [159]. These interactions help to explain the variation in PFAS behavior in soil, which is influenced by both the molecular structure of the compounds and the composition of the soil.

PFASs can change soil properties by reducing soil respiration and water stability while increasing pH, especially in soils with higher PFAS levels due to more alkalinity released during litter breakdown [160]. They also disrupt soil bacteria by increasing certain types like Firmicutes and Acidobacteria but reducing overall diversity and affecting enzyme activity, while also contaminating groundwater and plants, making it crucial to study their movement in soil [161].

PFAS movement and accumulation in soil are strongly influenced by soil properties and PFAS chemical structure. Soil organic carbon (SOC) content slows PFAS movement by increasing sorption, especially for long-chain PFASs, which bind more strongly to soil and are less mobile. In contrast, short-chain PFASs are more water-soluble, less strongly retained, and thus more mobile and more likely to be taken up and translocated by plants [162–164]. Plant root uptake and translocation depend on both PFAS properties and plant physiology: long-chain PFASs tend to accumulate in roots, while short-chain PFASs are more readily moved to shoots [163–165]. Soil amendments, such as clays or immobilization agents, can significantly reduce PFAS bioavailability and plant uptake, offering potential remediation strategies [166,167]. Additionally, factors like soil pH, cation concentration, and root distribution further modulate PFAS mobility and plant uptake [162,168].

PFASs exhibit complex behavior in soils that critically shapes their fate across environmental compartments. Soils act as major reservoirs for PFASs, with their retention and mobility governed by factors such as PFAS chain length, functional groups, soil organic matter, pH, and cation content. Longer-chain PFASs tend to sorb more strongly to soils, leading to prolonged residence times and potential for slow leaching to groundwater, while shorter-chain PFASs are more mobile and can migrate more readily to water bodies or be taken up by plants [75,169,170]. PFASs can enter soils via atmospheric deposition, contaminated water, or biosolids, and once present, they may be transferred to plants, enter terrestrial food webs, or leach into surface and groundwater, contributing to widespread environmental distribution and human exposure [75,171]. Interactions at air–water and solid–water interfaces, as well as with dissolved organic matter and co-contaminants, further influence PFAS partitioning and transport between soil, water, and air [172,173]. Soil thus serves not only as a sink but also as a long-term source, slowly releasing PFASs to other compartments and sustaining contamination cycles. The persistence, bioaccumulation, and potential for transformation or degradation of PFASs in soils and other media underscore the need for integrated, multi-compartmental approaches to understanding and managing their environmental fate [73,169–171].

5. Human Exposure Pathways and Bioaccumulation

Exposure to PFASs indoors occurs through ingestion of dust, inhalation, and dermal contact. Investigating indoor exposure is complex due to the variety of PFASs compounds, including precursors and polymers. Semivolatile PFASs are found in air, dust, and on various surfaces. Their distribution is primarily determined by their octanol–air partition coefficients, which influence how these compounds partition between the air and solid surfaces [174]. Some PFASs, like FTOH and perfluorooctane sulfonamidoethanol, are present in indoor air, while PFOA and PFOS accumulate in dust. Fluorinated polymers, such as side-chain fluoropolymers, may enter dust through abrasion or degradation [174,175]. The exact quantity of unidentified organic fluorine present in air and dust is still uncertain. Neutral PFASs were detected at all sampled locations, with FTOHs being the most prevalent, which aligns with earlier studies [176]. The PFAS profiles and their concentrations differed across the locations, likely as a result of variations in the types of PFAS-containing products present (Figure 2). Polyethylene (PE) sheets can serve as a useful tool to track changes in PFAS profiles and concentration levels across various indoor air environments.

Occupational exposures and communities near contaminated sites also face elevated PFAS risks [177]. Research has indicated that children are exposed to PFASs differently than adults, largely because of variations in their behavior and diet. Breastfeeding has been identified as a significant route for early-life PFAS exposure, which can contribute to higher levels in infants compared to adults [178,179].

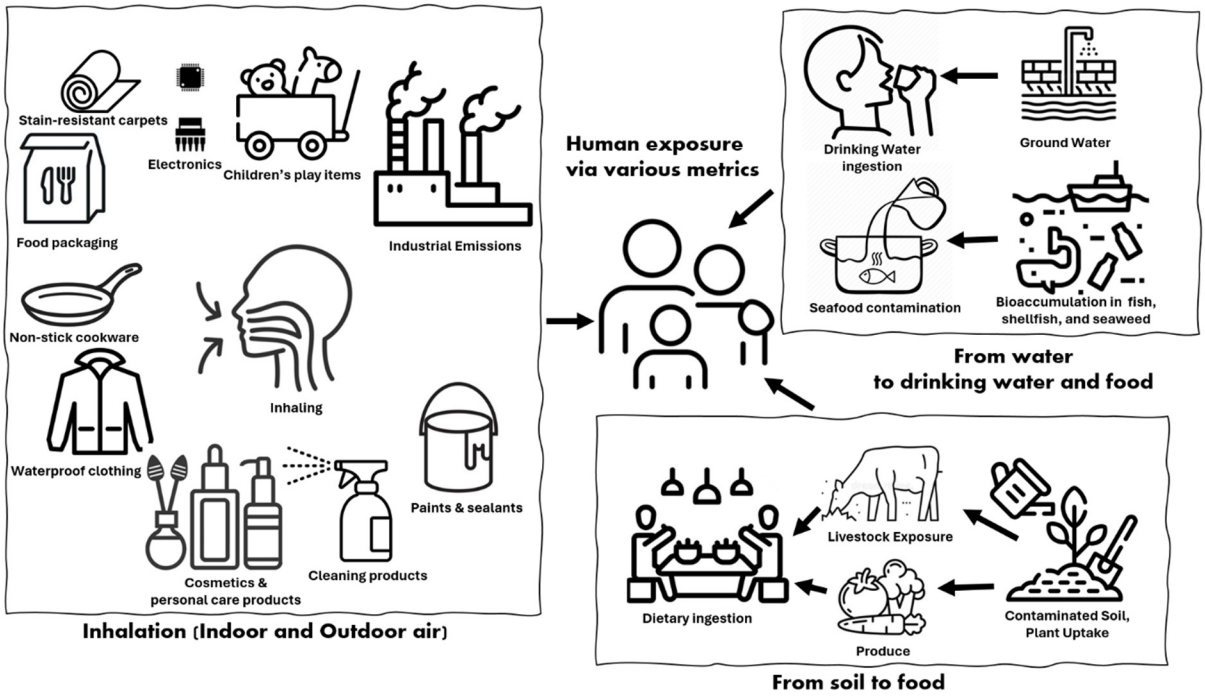

Figure 2. Pathways of human exposure to contaminants through air, water, and soil.

Indoor PFAS concentrations are typically assessed using filtration or solid-phase adsorption, followed by extraction for quantification [180,181]. Indoor air levels can be significantly higher than outdoor concentrations [176]. Dust samples often show high PFAS levels, including polyfluorinated phosphate esters [182]. However, indoor dust sampling methods are not standardized, and most studies use convenience sampling [183]. Inhalation exposure estimates are more reliable than dust ingestion due to uncertain ingestion rates [25]. Limited studies compare indoor exposure routes with dietary intake [179].

Outdoor PFAS air levels are lower than indoors but can be higher in urban areas [75]. Communities near emission sources, such as Parkersburg, WV, and Fayetteville, NC, have experienced PFAS air contamination affecting drinking water [76]. Dermal exposure to PFASs occurs through dust, personal care products, and cosmetics, though research is limited [184].

Biofilms facilitate PFAS bioaccumulation and transfer in freshwater ecosystems. PFASs adhere to biofilm surfaces, integrate into extracellular polymeric substances (EPS), or accumulate intracellularly [185]. Long-chain PFASs, particularly PFOS, are frequently detected in biofilms [186]. Biofilm composition, including protein and lipid content, influences PFAS accumulation and trophic transfer [187]. Despite limited research, biofilms could play a significant role in enhancing the bioavailability of PFASs within aquatic food webs [188].

Aquatic plants influence PFAS cycling by contributing organic carbon and potentially aiding phytoremediation. PFAS bioaccumulation depends on chemical properties, environmental factors, and sediment composition. Long-chain PFASs accumulate predominantly in roots, while short-chain PFASs translocate to shoots. Species-specific differences and habitat conditions affect PFAS accumulation patterns [189].

As noted by Ahrens et al. [190], PFASs in fish tend to accumulate predominantly in the blood and liver, with intermediate concentrations found in the gills, kidneys and intestines. However, the muscle tissue shows only trace amounts of PFASs. PFAS concentrations vary by tissue, with the highest levels in liver, followed by stomach and cheek [191]. Long-chain PFASs, particularly PFOS, dominate in fish, while short-chain PFASs, such as PFPeA, are more prevalent in omnivorous or herbivorous fish muscle, likely due to dietary exposure [192].

PFAS contamination in agricultural products like eggs, produce, fruits, dairy, and meat is mainly linked to soil pollution (Figure 2). Livestock consume PFASs through contaminated soil, plants, and feed. These chemicals have been detected in animal products such as eggs, milk, and meat [193]. In 2018, the European Food Safety Authority (EFSA) set a tolerable weekly intake (TWI) limit of 13 nanograms per kilogram of body weight for perfluorooctanoic acid (PFOA) and 6 nanograms per kilogram for perfluorooctanesulfonic acid (PFOS). However, in a later update, they lowered this limit to 4.4 ng per kg for the combined total of four PFASs [194]. Eggs contribute significantly to dietary PFAS exposure, particularly in children, where contributions to TWI range from 0 to 29% [193]. Free-range eggs contain higher PFAS levels due to soil exposure. In areas with contamination, PFOS concentrations in eggs can surpass 1000 ng per gram. Additionally, fresh produce and fruits can significantly contribute to PFAS exposure, particularly when irrigated with contaminated water [195].

PFASs are present in dairy milk, meat, and infant formula, with intake varying by location and age [196,197]. Meat consumption is associated with increased plasma PFAS levels, particularly PFUnDA, PFNA, and PFHxS. High-vegetable diets correlate with lower PFAS plasma levels, while high-fat meat diets increase PFOS and PFNA concentrations [198]. PFASs mainly enter the human body through food consumption, including sources like seafood, poultry, produce, and eggs, with the highest concentrations found in serum. The four primary PFASs share similar toxicokinetic characteristics, such as comparable accumulation patterns and relatively prolonged half-lives. According to the European Food Safety Authority [194], they typically produce the same effects within the body. However, there is still a lack of comprehensive data regarding the occurrence, persistence, and harmful effects of PFASs in humans, which complicates the ability to fully evaluate the risks of contamination, although the presence of risk is generally acknowledged. International policies rely on animal toxicity studies to estimate human health effects, using dose–response relationships. Direct comparisons between animal and human responses are important but difficult, as animals may react differently to the same chemicals. It is also worth noting that the concentrations shown to cause adverse effects are typically higher than those detected in the environment [199].

6. Health Effects of PFAS Exposure

Recent investigations have increasingly focused on the potential health implications of PFASs, with emerging evidence suggesting their widespread effects on multiple physiological systems. These studies have linked PFAS exposure to adverse outcomes in renal function, metabolic processes, respiratory health, immune responses, and thyroid regulation.

In the realm of lipid metabolism, PFAS exposure is robustly linked to dyslipidemia and altered lipid metabolism. Mechanistically, PFASs can activate peroxisome proliferator-activated receptor alpha (PPARα), disrupt nuclear receptor signaling, and interfere with genes regulating lipid and cholesterol homeostasis. These disruptions lead to increased circulating cholesterol, triglyceride accumulation, and changes in bile acid metabolism, as shown in both human and animal studies [90,200].

PFASs also cause thyroid hormone disruption by binding to thyroid hormone transport proteins, displacing thyroxine (T4), and interfering with thyroid peroxidase activity, leading to altered feedback in the hypothalamic–pituitary–thyroid axis. Epidemiological and experimental data indicate PFAS exposure is associated with changes in thyroid hormone levels, with some evidence of sex-specific effects and non-monotonic dose responses [200,201].

Furthermore, PFAS exposure leads to immune suppression, with multiple studies reporting significant associations between PFAS exposure and reduced immune function, particularly in children. Mechanisms include interference with immune cell signaling and suppression of antibody responses, though detailed molecular pathways remain under investigation [90,199–201].

Chen et al. [202] reported that PFOA might have an impact on renal tubules. Their research identified seven lipid molecules associated with the connection between PFOA and uric acid (UA). A significant positive correlation was found between kidney function markers and certain lipid subclasses, including fatty acids, their conjugates, fatty acid esters, and sesquiterpenoids.

Yang et al. [203] found that higher plasma concentrations of PFOS, PFHxS, and total PFASs were linked to an elevated hepatic steatosis index, indicating an increased likelihood of developing metabolic-associated fatty liver disease (MAFLD).

Regarding kidney disease, Zhang et al. [204] compared long-chain and short-chain PFASs, highlighting that short-chain PFASs, such as perfluorobutyric acid (PFBA), have a shorter half-life in blood and do not accumulate as extensively in kidney tissue. In contrast, PFOS was found to be more prevalent in human kidneys.

Studies have also linked PFAS exposure to respiratory conditions. Qin et al. [205] identified associations between PFOS, PFOA, PFNA, and PFHxS exposure and asthma, while Kvalem et al. [206] specifically observed a link between PFHpA exposure and asthma in girls.

Von Holst et al. [207] investigated the immunosuppressive effects of PFAS exposure in children, focusing on compounds such as PFOS, PFOA, and potentially PFHxS and PFNA. Their findings suggested a potential reduction in vaccine efficacy due to PFAS-related immune interference. Higher maternal PFAS levels were associated with reduced antibody responses to vaccines in young children, with early indications suggesting that PFOS exposure might increase the risk of infections.

Nian et al. [208] found stronger associations between exposure to PFBS and PFHpA and elevated levels of fetal gonadotropins and sex hormone-binding globulin (SHBG), in contrast to long-chain PFASs. In addition, Gao et al. [209] observed that short-chain PFASs, such as PFBA and PFHpA, had more pronounced negative effects on birth weight and length when detected in both maternal and cord blood, compared to long-chain PFASs.

In young adults, exposure to PFASs, especially PFOA, has been associated with increased breakdown of fats and oxidation of fatty acids, potentially leading to disrupted glucose metabolism [210]. Similarly, Yu et al. [211] identified strong associations in cross-sectional data between higher levels of PFOS, PFOA, PFHxS, and Et-PFOSA-AcOH and increased HOMA-β, a marker of pancreatic β-cell function. However, only PFOA and PFHxS showed a significant link to refined insulin response measures, such as the insulinogenic index.

A prospective study by Halldorsson et al. [212] revealed that elevated prenatal plasma PFOA levels were linked to an increased incidence of overweight and greater waist circumference in female offspring at 20 years of age, though no such connection was observed in males. Furthermore, PFOA exposure during pregnancy was linked to elevated insulin and leptin levels, as well as lower adiponectin levels, in female offspring at the same age.

Research on the relationship between PFAS exposure and cancer has also been explored. Vieira et al. [213] analyzed perfluorooctanoic acid (PFOA) exposure and cancer risks, noting that the most extensive long-term cohort study on this topic was conducted in the Mid-Ohio Valley [213]. Other large population-based cohorts, such as those in Ronneby, Sweden (PFHxS and PFOS exposure; [214]) and Veneto, Italy (PFOA exposure; [215]), provide additional research opportunities.

Zhang et al. [216] conducted a meta-analysis of 13 studies to evaluate the effects of PFAS exposure on thyroid hormones during pregnancy. Their results showed a consistent link between exposure to PFOS, PFOA, and PFDA and increased levels of maternal thyroid-stimulating hormone (TSH). In a separate study, Fini et al. [217] examined the impact of chemical exposures, including PFOA and PFOS, on thyroid hormone signaling in Xenopus laevis embryos. The findings suggested that PFAS exposure, at concentrations similar to those found in human amniotic fluid, could interfere with thyroid hormone-dependent

processes, affecting gene expression, transcription, and brain development during the early stages of embryogenesis.

The growing body of research highlights the pervasive and long-lasting health effects of PFAS exposure, which span across multiple physiological systems. These substances have been linked to metabolic disorders such as obesity and diabetes, endocrine disruption, respiratory conditions, reproductive challenges, and even neurological impairments. Notably, studies have underscored the heightened vulnerability of children and pregnant women to PFASs, with implications for fertility, cognitive development, and immune function. Further, the accumulation of PFASs in human tissues has raised concerns about their role in cancer development and genetic mutations passed on to future generations.

The global contamination trends outlined in the previous tables, particularly the widespread presence of PFASs in water sources as shown in Table 3, directly correlate with the severe health outcomes summarized here. Table 4 underscores that PFAS exposure presents a systemic, multi-organ health threat, with the most frequent and severe risks (rated "High") affecting nearly every major bodily system. Long-term effects are predominant, including endocrine disruption, metabolic disorders, reproductive harm, neurological impairment, immune dysfunction, and cancer. Critically, the health impacts are life-stage specific: children face increased risks of respiratory, immune, and developmental issues, while adults and the elderly are more vulnerable to metabolic, cardiovascular, and bone diseases. This comprehensive health profile highlights that PFASs are not merely environmental pollutants but a profound and persistent public health crisis, with potential generational impacts due to epigenetic changes.

Table 4. Health effects of PFAS exposure—risk assessment and long-term impact.

Health Outcome	Evidence and Effects	Risk Level	Affected Group	Impact Type	Reference
Toxicokinetics	Uptake Via water, soil, food; persists in organs.	High	Both	Long-term accumulation	[218,219]
Respiratory	Asthma, lung function decline in children.	Moderate	Children	Short-term respiratory issues	[220]
Endocrine Disruption	Affects thyroid, sex hormones, cortisol levels.	High	Both	Long-term hormonal imbalance	[221,222]
Metabolic Effects	Alters glucose, lipids, diabetes.	High	Both	Long-term metabolic disorders	[223]
Reproductive	Impaired fertility, miscarriage, developmental issues.	High	Pregnant women, children	Long-term fertility issues	[224]
Neurological	ADHD, cognitive decline, Parkinson's, Alzheimer's.	High	Children, elderly	Long-term cognitive impairment	[225]
Bone Health	Osteoporosis risk, bone density loss.	Moderate	Elderly	Long-term bone weakness	[226]
Obesity	Increased obesity risk in offspring.	Moderate	Children	Long-term weight gain	[227]
Lipid Metabolism	Affects cholesterol, linked to cardiovascular disease.	High	Adults	Long-term cardiovascular effects	[228]
Kidney disease	Chronic kidney disease	Moderate	Adults	Long-term kidney damage	[229]
Cardiovascular Health	Linked to hypertension but not coronary heart disease.	Moderate	Adults	Long-term cardiovascular issues	[228]
Cerebrovascular	Links to stroke and cerebrovascular problems.	Moderate	Adults	Long-term stroke risk	[230]
Diabetes	Limited study about linking to Type 2 diabetes.	Low	Adults	Uncertain long-term impact	[231]
Liver Disease	Links to liver dysfunction, NAFLD, cirrhosis.	Moderate	Adults	Long-term liver complications	[232]
Immune System	Reduces immune function, increases autoimmune diseases.	High	Children	Long-term immune dysfunction	[233]
Cancer Risk	testicular, breast cancer.	High	Adults	Long-term cancer risk	[234,235]
Genetic Effects	Epigenetic changes passed to future generations.	High	Future Generations	Long-term generational effects	[236]

N.B: In this Table 4, "High" indicates a strong association with severe health outcomes based on consistent evidence; "Moderate" signifies a clear link but with less certainty or severity; and "Low" denotes a potential but uncertain or limited connection.

The evidence underscores the critical need for continued research and a proactive approach to mitigate PFAS exposure, particularly given their persistence in the environment and human body. The findings also call for greater public awareness, stronger regulations on industrial emissions, and improved water and food safety standards. Addressing PFAS contamination is essential for safeguarding both public health and environmental well-being.

Based on the evidence, the dominant exposure routes for PFASs are contaminated drinking water and food chains, disproportionately affecting communities near industrial sites. Key vulnerable populations include children, due to their developing systems and heightened susceptibility to developmental and immune effects, and pregnant women, with risks extending to their offspring. A primary concern is PFAS bioaccumulation in the body, leading to long-term exposure from even short-term contact and facilitating a range of severe, multi-generational health issues.

7. Knowledge Gaps and Research Needs

7.1. PFAS Applications and Use Data

This study examines various past and present uses of PFASs, but the list is not exhaustive and contains some uncertainties. One major uncertainty is the challenge of aligning data from different sources into a single-use category. This is particularly important when comparing usage quantities, as the categories in different databases may vary. For example, some categories, particularly those in the Chemical Data Reporting database under the TSCA, are too broad to be classified into a specific category for this study. As a result, there may be discrepancies in the way PFAS applications are categorized and quantified across sources. Although patents provide a lot of information, only some of the PFASs mentioned are likely being used in the market today. There may also be missing subcategories, and some uses of PFASs may no longer be in use. To improve the list of uses in the future, one option could be to look at product registries from as many countries as possible and integrate these data with industrial production and trade statistics for better accuracy.

7.2. Exposure Assessment Gaps

There are varying PFAS exposure levels indoors and outdoors, inconsistent sampling methods, and differences in PFAS-containing products. Difficulties arise from limited research on biofilms, dermal exposure, and food contamination. Estimating ingestion and inhalation rates also remains challenging due to insufficient standardized data. In addition, more research is needed to link environmental fate processes (e.g., atmospheric transport, soil leaching, and wastewater pathways) with human exposure scenarios. Zheng et al. [184] mentioned that dermal exposure to PFASs occurs through dust, personal care products, and cosmetics, but research on this topic is limited. However, dermal exposure from products and dust does provide a direct absorption route, and thus this is a critical area that needs to be addressed. Biofilms act as environmental reservoirs, concentrating PFASs and facilitating their movement into the food web. Understanding these pathways is essential to accurately quantifying total human exposure, which is the foundation for evaluating health risks and setting protective safety standards.

7.3. Health Effects Uncertainties

This health study faces uncertainties due to inconsistent evidence on some health effects, such as diabetes, stroke, and thyroid disease. The difficulty arises in proving a direct link between PFAS exposure and specific diseases, as multiple factors influence health outcomes. Long-term effects, especially generational impacts, are hard to measure. Variability in exposure levels among populations adds complexity. Differences in study methods and sample sizes create inconsistencies. Lack of standardized testing for PFAS

levels in humans also limits accuracy. Lastly, ethical concerns prevent controlled exposure studies, making it difficult to establish definite cause-and-effect relationships for many health conditions.

7.4. Proportion of Studies Lacking Standardization

Significant gaps exist in PFAS research, with only a small fraction of the thousands of known PFAS compounds being routinely studied—most human and wildlife exposure assessments focus on just 2–30 legacy PFASs, leaving the uses and risks of the vast majority unknown [90,237,238]. For example, hundreds to thousands of PFASs are used in global commerce, but analytical methods and available standards lag behind, making it difficult to even identify or quantify many compounds [90,237]. In environmental and biomonitoring studies, up to 48% of total organofluorine in human plasma remains unaccounted for, indicating that a substantial proportion of exposure is from unidentified PFASs [90]. Exposure estimates can vary by two orders of magnitude due to uncertainties in source contributions and lack of standardized methods [90]. Only about seven studies have provided paired data on indoor PFAS exposure and human serum, and most studies are limited by small sample sizes, non-representative populations, and inconsistent reporting, further compounding uncertainty [239]. In wildlife, 97% of studies focus on PFOS, 91% on PFOA, and very few on new-generation PFASs, with notable geographic and taxonomic gaps—most research is concentrated in high-income countries and aquatic habitats, leaving mid- and low-income regions and invertebrates understudied [238]. Overall, the lack of standardization, limited compound coverage, and variability in exposure estimates highlight the magnitude of the problem and the urgent need for broader, harmonized research efforts.

7.5. Recommendations for Future Research

To address the challenges in PFAS research, future studies should focus on standardizing data collection and categorization across various databases to ensure consistency in comparing PFAS applications and exposure levels. Expanding product registries globally would help to capture a more complete picture of PFAS uses and their evolution over time. Research on PFAS exposure should be broadened to include biofilms, dermal contact, and food contamination, with standardized methods for estimating ingestion and inhalation rates. Linking exposure studies with environmental fate models will also strengthen risk assessments. Health studies would benefit from standardized testing protocols for PFAS levels in humans, allowing for more accurate assessments of health risks. Additionally, long-term studies are necessary to evaluate generational impacts, as current research often lacks data on these effects. Ethical barriers to controlled exposure studies could be addressed by focusing on observational or retrospective studies. Finally, increased global collaboration and research funding are essential to improving methodologies and our understanding of PFASs' impacts on both human health and the environment.

8. Conclusions

8.1. Improving the Standardization of Detection

This review provides a detailed analysis of PFASs, focusing on their widespread use in various industries, their persistence in the environment, and the risks they pose to human health. Despite significant progress in research, many aspects of PFAS behavior and their long-term effects remain poorly understood, highlighting the need for further investigation.

One of the most important areas for improvement is the development of better methods to detect PFASs at low levels in the environment and in human tissues. Advanced technologies such as mass spectrometry and fluorescence-based sensors could be improved to monitor PFAS contamination more accurately. Moreover, solutions like bioremediation,

which involves using microorganisms to break down PFASs, should be explored to clean up contaminated areas, particularly water and soil. Additionally, improving filtration systems to remove PFASs from drinking water is a critical next step in managing contamination.

8.2. Empowering Through Information and Policy

PFAS contamination presents a global health challenge, with regions like Canada and Germany showing extreme levels, particularly from industrial discharges, while Afghanistan and other areas report minimal contamination. In addition to technological advancements, regulatory measures must evolve to better control PFAS emissions and limit their use in products. Governments should establish stricter regulations to manage the release of PFASs from industries and reduce their presence in everyday products. This should also include promoting innovation in industrial sectors to identify safer alternatives and sustainable practices, minimizing reliance on PFASs in manufacturing. Such actions would help to minimize exposure and prevent further contamination of the environment.

Public awareness and education are also key to reducing exposure. Consumers need to be informed about the risks associated with products that contain PFASs, such as food packaging, textiles, and cosmetics. Clear labeling of PFAS-free products will allow consumers to make more informed choices. Additionally, policymakers need to understand the importance of regulating PFASs and implementing measures to protect public health from these chemicals. Vulnerable populations, such as children, pregnant women, and communities living near contaminated industrial sites, are particularly at risk. More research is needed to understand the specific impacts of PFAS exposure on these groups, particularly regarding developmental health, neurodevelopment, and reproductive outcomes. Identifying these risks will help to guide policies and interventions aimed at protecting these sensitive populations.

8.3. Health Effects: Prioritizing Vulnerable Populations and Targeted Research

The documented health risks of PFASs, including potential developmental, reproductive, and immunological effects, are not distributed equally across the population. To safeguard those most at risk, targeted action is required. A paramount actionable step is to direct future research efforts towards understanding the specific impacts of PFAS exposure on vulnerable groups, such as children, pregnant women, and communities near contaminated industrial sites. Focusing on developmental health, neurodevelopment, and reproductive outcomes will generate the critical data needed to guide precise public health interventions, refine safety standards, and develop protective policies specifically designed for these sensitive populations.

While significant strides have been made in understanding PFASs, there is still much work to be done. Future studies must integrate insights from industrial applications, environmental fate, human exposure, and health effects to provide a holistic understanding of PFASs' impacts. A coordinated approach involving research, better regulation, public education, and the development of safer alternatives is essential to reduce the risks of PFASs and protect both human health and the environment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pollutants5040043/s1, Table S1: Summary of selected physicochemical properties of most common PFAS. References [240–243] are cited in the Supplementary Materials.

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References

1. Buck, R.C.; Franklin, J.; Berger, U.; Conder, J.M.; Cousins, I.T.; de Voogt, P.; Jensen, A.A.; Kannan, K.; Mabury, S.A.; van Leeuwen, S.P. Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. *Integr. Environ. Assess. Manag.* **2011**, *7*, 513–541. [CrossRef]
2. Gaines, L.G.T. Historical and current usage of per- and polyfluoroalkyl substances (PFAS): A literature review. *Am. J. Ind. Med.* **2023**, *66*, 353–378. [CrossRef]
3. Gardiner, J. Fluoropolymers: Origin, Production, and Industrial and Commercial Applications. *Aust. J. Chem.* **2015**, *68*, 13. [CrossRef]
4. Schellenberger, S.; Hill, P.J.; Levenstam, O.; Gillgard, P.; Cousins, I.T.; Taylor, M.; Blackburn, R.S. Highly fluorinated chemicals in functional textiles can be replaced by re-evaluating liquid repellency and end-user requirements. *J. Clean. Prod.* **2019**, *217*, 134–143. [CrossRef]
5. Scheringer, M.; Trier, X.; Cousins, I.T.; de Voogt, P.; Fletcher, T.; Wang, Z.; Webster, T.F. Helsingør Statement on poly- and perfluorinated alkyl substances (PFASs). *Chemosphere* **2014**, *114*, 337–339. [CrossRef]
6. Glüge, J.; Scheringer, M.; Cousins, I.T.; DeWitt, J.C.; Goldenman, G.; Herzke, D.; Lohmann, R.; Ng, C.A.; Trier, X.; Wang, Z. An overview of the uses of per- and polyfluoroalkyl substances (PFAS). *Environ. Sci. Process. Impacts* **2020**, *22*, 2345–2373. [CrossRef] [PubMed]
7. Abunada, Z.; Alazaiza, M.Y.; Bashir, M.J. An overview of per-and polyfluoroalkyl substances (PFAS) in the environment: Source, fate, risk and regulations. *Water* **2020**, *12*, 3590. [CrossRef]
8. Knepper, T.P.E.; Lange, F.T. (Eds.) Polyfluorinated Chemicals and Transformation Products. In *The Handbook of Environmental Chemistry*; Springer: Berlin/Heidelberg, Germany, 2012; Volume 17, No. 17.
9. United Nations Environment Programme. Guidance on Alternatives to Perfluorooctane Sulfonic Acid and Its Derivatives. In Proceedings of the Persistent Organic Pollutants Review Committee on the Work of Its Sixth Meeting, Geneva, Switzerland, 15 October 2010.
10. Habib, A. Green Analytical Methods for the Determination of Perfluorocarboxylic Acids (PFCAs) and Fluorotelomer Alcohols (FTOHs) in Water. Ph.D. Thesis, The University of Texas at El Paso, El Paso, TX, USA, 2023.
11. Sun, M.; Arevalo, E.; Strynar, M.; Lindstrom, A.; Richardson, M.; Kearns, B.; Pickett, A.; Smith, C.; Knappe, D.R.U. Legacy and Emerging Perfluoroalkyl Substances Are Important Drinking Water Contaminants in the Cape Fear River Watershed of North Carolina. *Environ. Sci. Technol. Lett.* **2016**, *3*, 415–419. [CrossRef]
12. Wang, Y.; Chang, W.; Wang, L.; Zhang, Y.; Zhang, Y.; Wang, M.; Wang, Y.; Li, P. A review of sources, multimedia distribution and health risks of novel fluorinated alternatives. *Ecotoxicol. Environ. Saf.* **2019**, *182*, 109402. [CrossRef]
13. U.S. FDA. Indirect Food Additives: Paper and Paperboard Components. In *FDA*, 21st ed.; CFR Part 176; Federal Register; U.S. FDA: Silver Spring, MD, USA, 2016; Volume 81, FR 5.
14. Kissa, E. *Fluorinated Surfactants and Repellents*; Marcel Dekker, Inc.: New York, NY, USA, 2001.
15. 3M. 3M Novec Contact Cleaner Safety Data Sheet. 3M Company. 2024. Available online: https://www.3m.com/3M/en_US/company-us/SDS-search/results/?gsaAction=msdsSRA&msdsLocale=en_US&co=ptn&q=novec (accessed on 27 October 2025).
16. 3M. 3M Novec Flux Remover Safety Data Sheet. 3M Company. 2023. Available online: https://multimedia.3m.com/mws/mediawebserver?mwsId=SSSSSuUn_zu8l00xm8tBm8m9Pv70k17zHvu9lxtD7SSSSSS-- (accessed on 27 October 2025).
17. Dias, D.; Bons, J.; Kumar, A.; Kabir, M.H.; Liang, H. Forever chemicals, per-and polyfluoroalkyl substances (PFAS) in lubrication. *Lubricants* **2024**, *12*, 114. [CrossRef]
18. Dhanda, A.; Yadav, S.; Ghangrekar, M.M. Properties, Uses, Sources, and Environmental Releases of Per-and Polyfluoroalkyl Substances. *PFAS Environ. Occur. Charact. Treat. Manag.* **2025**, *2*, 17–33.
19. Caslavsky, V.; Gron, P. Method of Inhibiting the Formation of Plaque. U.S. Patent 5,100,649, 31 March 1992.
20. Cansell, F.; Aymonier, C.; Loppinet-Serani, A. Review on materials science and supercritical fluids. *Curr. Opin. Solid State Mater. Sci.* **2003**, *7*, 331–340. [CrossRef]
21. Alam, M.J.; Ahamed, M.S.; Islam, M.S.; Halim, M.E.; Uddin, K.M. Computational study of nickel complexes: Stability and electronic charge insights. *Am. J. Pure Appl. Sci.* **2025**, *7*, 213–220. [CrossRef]
22. Zohora, F.T.; Wasif, A.; Hussain, A.; Alam, M.J.; Debnath, T.; Halim, M.E. Synthesis, Characterization, and Computational Studies of Salophh2-Metal Complexes: Structural and Electronic Properties with Stability Insights. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5228206 (accessed on 25 October 2025).
23. Ebnesajjad, S. *Introduction to Fluoropolymers: Materials, Technology, and Applications*; William Andrew: Norwich, NY, USA, 2020.

24. OECD. *Synthesis Paper on Per- and Polyfluorinated Chemicals*; OECD Publishing: Paris, France, 2013. [CrossRef]
25. U.S. Environmental Protection Agency (EPA). *Compliance Guide for Surface Coatings Subject to the Long-Chain Perfluoroalkyl Carboxylate and Perfluoroalkyl Sulfonate Chemical Substances Significant New Use Rule*; EPA: Washington, DC, USA, 2021. Available online: https://www.epa.gov/sites/default/files/2021-01/documents/final_lcpfac-snur_surface-coating-compliance-guide_0.pdf (accessed on 27 August 2025).
26. Plassmann, M.M.; Berger, U. Perfluoroalkyl carboxylic acids with up to 22 carbon atoms in snow and soil samples from a ski area. *Chemosphere* **2013**, *91*, 832–837. [CrossRef]
27. Daikin. Fluoroelastomers. 2025. Available online: https://www.daikinchemicals.com/solutions/products/dai-el-fluoroelastomers.html (accessed on 15 January 2025).
28. Mansfield, C.; Hughes, J.; Gurevich, E.; Ux, B.; Quartapella, C. Fast Curing Fluoroelastomeric Compositions, Adhesive Fluoroelastomeric Compositions and Methods for Bonding Fluoroelastomeric Compositions. U.S. Patent 7,514,506 B2, 7 April 2009.
29. Nguyen, T.; Nesci, K. EPA's Analytical Chemistry Branch PFAS Testing, Rinses from Selected Fluorinated and Non-Fluorinated HDPE Containers. 2021. Available online: https://www.epa.gov/sites/default/files/2021-03/documents/results-of-rinsates-samples_03042021.pdf (accessed on 21 June 2025).
30. Saito, S.; Ohno, O.; Igarashi, S.; Kato, T.; Yamaguchi, H. Separation and Recycling for Rare Earth Elements by Homogeneous Liquid-Liquid Extraction (HoLLE) Using a pH-Responsive Fluorine-Based Surfactant. *Metals* **2015**, *5*, 1543–1552. [CrossRef]
31. Lacanau, V.; Bonneté, F.; Wagner, P.; Schmitt, M.; Meyer, D.; Bihel, F.; Contino-Pépin, C.; Bourgeois, D. From Electronic Waste to Suzuki−Miyaura Cross-Coupling Reaction in Water: Direct Valuation of Recycled Palladium in Catalysis. *ChemSusChem* **2020**, *13*, 5224–5230. [CrossRef] [PubMed]
32. Kato, T.; Saito, S.; Oshite, S.; Igarashi, S. Powerful Concentration of Rhodium in Plating Wastewater Using Homogeneous Liquid–Liquid Extraction (HoLLE) and Study for Scale-up. *Environ. Nat. Resour. Res.* **2017**, *7*, 44. [CrossRef]
33. Leybros, A.; Segond, N.; Grandjean, A. Remediation of 137Cs-contaminated concrete rubble by supercritical CO_2 extraction. *Chemosphere* **2018**, *208*, 838–845. [CrossRef]
34. Park, K.; Kim, T.; Park, J.; Yan, X.; Kim, H. Development of a carbamate-conjugated catechol ligand and its application to Cs extraction from contaminated soil by using supercritical CO_2. *Chemosphere* **2020**, *242*, 125210. [CrossRef]
35. Lin, Y.; Wai, C.M. Supercritical Fluid Extraction of Lanthanides with Fluorinated beta. Diketones and Tributyl Phosphate. *Anal. Chem.* **1994**, *66*, 1971–1975. [CrossRef]
36. Wang, S.; Lin, Y.; Wai, C.M. Supercritical Fluid Extraction of Toxic Heavy Metals from Solid and Aqueous Matrices. *Sep. Sci. Technol.* **2003**, *38*, 2279–2289. [CrossRef]
37. Xiao, X.; Yan, B.; Fu, J.; Xiao, X. Absorption and recovery of n-hexane in aqueous solutions of fluorocarbon surfactants. *J. Environ. Sci.* **2015**, *37*, 163–171. [CrossRef]
38. U.S. Environmental Protection Agency. CompTox Chemicals Dashboard. Retrieved 20 January 2025. Available online: https://comptox.epa.gov/dashboard (accessed on 14 July 2025).
39. Aoki, Y. Method for Producing Amide Derivative. U.S. Patent 9,890,110 B2, 13 February 2018.
40. U.S. EPA. Inert Ingredient; Revocation of the Tolerance Exemption for Mono- and Bis-(1H, 1H, 2H, 2H-perfluoroalkyl) Phosphates Where the Alkyl Group is Even Numbered and in the C6-C12 Range. In *Federal Register*; EPA US, ed.; EPA: Washington, DC, USA, 2006; 40 CFR Part 180; Volume EPA-HQ-OPP-2006-0253, pp. 45408–45411.
41. Sawyer, W.; Rowe, K.; Webber, A. Coated Particles, Methods of Making the Same, and Methods of Use. U.S. Patent 9,174,886 B2, 3 November 2015.
42. Boyd, J. *Fujitsu Liquid Immersion Not All Hot Air When It Comes to Cooling Data Centers*; IEEE Spectrum: New York, NY, USA, 2017.
43. Ebnesajjad, S.; Snow, L.G. Fluorine-Containing Polymers, Poly(Vinyl Fluoride). In *Kirk-Othmer Encyclopedia of Chemical Technology*; Wiley: Hoboken, NJ, USA, 2000. [CrossRef]
44. Ivanchev, S.S.; Likhomanov, V.S.; Primachenko, O.N.; Khaikin, S.Y.; Barabanov, V.G.; Kornilov, V.V.; Odinokov, A.S.; Kulvelis, Y.V.; Lebedev, V.T.; Trunov, V.A. Scientific principles of a new process for manufacturing perfluorinated polymer electrolytes for fuel cells. *Pet. Chem.* **2012**, *52*, 453–461. [CrossRef]
45. Clark, L.C.; Gollan, F. Survival of Mammals Breathing Organic Liquids Equilibrated with Oxygen at Atmospheric Pressure. *Science* **1966**, *152*, 1755–1756. [CrossRef] [PubMed]
46. Mayer, D.; Ferenz, K.B. Perfluorocarbons for the treatment of decompression illness: How to bridge the gap between theory and practice. *Eur. J. Appl. Physiol.* **2019**, *119*, 2421–2433. [CrossRef] [PubMed]
47. Okabe, R.; Chen-Yoshikawa, T.F.; Yoneyama, Y.; Yokoyama, Y.; Tanaka, S.; Yoshizawa, A.; Thompson, W.L.; Kannan, G.; Kobayashi, E.; Date, H.; et al. Mammalian enteral ventilation ameliorates respiratory failure. *Med* **2021**, *2*, 773–783.e5. [CrossRef] [PubMed]
48. Kaufman, R.J.; Richard, T.J.; Stephens, R.A.; Goodin, T.H.; Allen, J.S.; Layton, T.E. Homogeneous Water-in-Perfluorochemical Stable Liquid Dispersion for Administration of a Drug to the Lung of an Animal. U.S. Patent 5,770,585, 23 June 1998.

49. Maevsky, E.I.; Ivanitsky, G.R.; Makarov, K.N.; Kulakova, G.M.; Arkhipov, V.V.; Moroz, V.V.; Starovoitova, L.N.; Senina, R.Y.; Pushkin, S.J.; Ivashina, A.I. Emulsion of Perfluoroorganic Compounds for Medical Purposes, a Process for the Preparation Thereof and Methods for Treating and Preventing Diseases with the Use Thereof. U.S. Patent 6,562,872 B1, 13 May 2003.
50. Sabid, A.M.; Kamrul, H.M. Computational and Theoretical Analysis on the Single Proton Transfer Process in Adenine Base by Using DFT Theory and Thermodynamics. *IOSR J. Appl. Chem.* **2024**, *17*, 26–31.
51. Garrelts, J.C. Fluosol: An Oxygen-Delivery Fluid for use in Percutaneous Transluminal Coronary Angioplasty. *DICP* **1990**, *24*, 1105–1112. [CrossRef]
52. Zhang, C.; Yan, K.; Fu, C.; Peng, H.; Hawker, C.J.; Whittaker, A.K. Biological Utility of Fluorinated Compounds: From Materials Design to Molecular Imaging, Therapeutics and Environmental Remediation. *Chem. Rev.* **2022**, *122*, 167–208. [CrossRef]
53. Tressaud, A.; Haufe, G. (Eds.) *Fluorine and Health: Molecular Imaging, Biomedical Materials and Pharmaceuticals*; Elsevier: New York, NY, USA, 2008.
54. Schirmer, H.; Weinmann, H.J.; Platzek, J. Perfluoroalkyl-Containing Complexes, Process for Their Production as Well as Their Use. U.S. Patent 2007/0020183 A1, 17 November 2007.
55. Zheng, Q.; Yang, S.; Zhang, Y.; Wu, R.; Pang, J.; Li, W. Vitreous surgery for macular hole-related retinal detachment after phacoemulsification cataract extraction: 10-year retrospective review. *Eye* **2012**, *26*, 1058–1064. [CrossRef]
56. Guo, R.; Reiner, E.J.; Bhavsar, S.P.; Helm, P.A.; Mabury, S.A.; Braekevelt, E.; Tittlemier, S.A. Determination of polyfluoroalkyl phosphoric acid diesters, perfluoroalkyl phosphonic acids, perfluoroalkyl phosphinic acids, perfluoroalkyl carboxylic acids, and perfluoroalkane sulfonic acids in lake trout from the Great Lakes region. *Anal. Bioanal. Chem.* **2012**, *404*, 2699–2709. [CrossRef]
57. Leland Stanford Junior University. BioPortal. Retrieved 10 February 2025. 2024. Available online: https://bioportal.bioontology.org/ (accessed on 21 June 2025).
58. Liu, Y.; Huang, W. Stretchable Electrochemical Sensors for Cell and Tissue Detection. *Angew. Chem. Int. Ed.* **2021**, *60*, 2757–2767. [CrossRef] [PubMed]
59. Ellis, E.J.; Ellis, J.Y. Fluorine Containing Polymeric Compositions Useful in Contact Lenses. U.S. Patent 4,996,275, 11 August 1991.
60. Olufayo, O.A.; Abou-El-Hossein, K.; Kadernani, M.M. Tribo-electric Charging in the Ultra-high Precision Machining of Contact Lens Polymers. *Procedia Mater. Sci.* **2014**, *6*, 194–201. [CrossRef]
61. Paulson, K. Final Report for the Use of Wetting Agents/Fume Suppressants for Minimizing the Atmospheric Emissions from Hard Chromium Electroplating Baths 2004. TR-2243-ENV. 2004. Available online: https://apps.dtic.mil/sti/tr/pdf/ADA423561.pdf (accessed on 14 June 2025).
62. MI EGLE. Targeted and Nontargeted Analysis of PFAS in Fume Suppressant Products at Chrome Plating Facilities 2020. 2020. Available online: https://www.michigan.gov/documents/egle/wrd-ep-pfas-chrome-plating_693686_7.pdf (accessed on 20 August 2025).
63. Hepfer, I. Pre-Plating Conditioning Process. U.S. Patent No. 3,515,649, 2 June 1970. Available online: https://patents.google.com/patent/US3515649A (accessed on 20 June 2025).
64. Murphy, P.M.; Hewat, T. Fluorosurfactants in Enhanced Oil Recovery. *Open Pet. Eng. J.* **2008**, *1*, 58–61. [CrossRef]
65. Koch, E.-C. *Metal-Fluorocarbon Based Energetic Materials*; Wiley-VCH Verlag & Co.: Weinheim, Germany, 2012.
66. Prevedouros, K.; Cousins, I.T.; Buck, R.C.; Korzeniowski, S.H. Sources, fate and transport of perfluorocarboxylates. *Environ. Sci. Technol.* **2006**, *40*, 32–44. [CrossRef]
67. Chemguard Specialty Chemical Brochure. 2024. Available online: https://www.nationalfire.com/media/product_files/Chemguard_Brochure.pdf (accessed on 30 October 2024).
68. Kirsch, P. *Modern Fluoroorganic Chemistry: Synthesis, Reactivity, Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
69. Krafft, M.P. Fluorocarbons and fluorinated amphiphiles in drug delivery and biomedical research. *Adv. Drug Deliv. Rev.* **2001**, *47*, 209–228. [CrossRef] [PubMed]
70. Lide, D.R. *CRC Handbook of Chemistry and Physics*; Lide, D.R., Ed.; CRC Press: Boca Raton, FL, USA, 2006.
71. Politzer, P.; Jin, P.; Murray, J.S. Atomic polarizability, volume, and ionization energy. *J. Chem. Phys.* **2002**, *117*, 8197–8202. [CrossRef]
72. Ömür-Özbek, P.; Dietrich, A.M. Determination of temperature-dependent Henry's law constants of odorous contaminants and their application to human perception. *Environ. Sci. Technol.* **2005**, *39*, 3957–3963. [CrossRef]
73. Evangelou, M.W.; Robinson, B.H. The phytomanagement of PFAS-contaminated land. *Int. J. Environ. Res. Public Health* **2022**, *19*, 6817. [CrossRef]
74. Hammer, M.A.; Endo, S. Henry's law constants of 15 per-and polyfluoroalkyl substances determined by static headspace analysis. *J. Hazard. Mater. Lett.* **2022**, *3*, 100070.
75. Evich, M.G.; Davis, M.J.; McCord, J.P.; Acrey, B.; Awkerman, J.A.; Knappe, D.R.; Lindstrom, A.B.; Speth, T.F.; Tebes-Stevens, C.; Strynar, M.J. Per-and polyfluoroalkyl substances in the environment. *Science* **2022**, *375*, eabg9065. [CrossRef] [PubMed]
76. U.S. EPA. Technical fact sheet—Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). In *Office of Land and Emergency Management*; Environmental Protection Agency, Ed.; United States Environmental Protection Agency: Washington, DC, USA, 2017; EPA 505-F-17-001.

77. Jahnke, A.; Ahrens, L.; Ebinghaus, R.; Temme, C. Urban versus remote air concentrations of fluorotelomer alcohols and other polyfluorinated alkyl substances in Germany. *Environ. Sci. Technol.* **2007**, *41*, 745–752. [CrossRef]
78. Davis, K.L.; Aucoin, M.D.; Larsen, B.S.; Kaiser, M.A.; Hartten, A.S. Transport of ammonium perfluorooctanoate in environmental media near a fluoropolymer manufacturing facility. *Chemosphere* **2007**, *67*, 2011–2019. [CrossRef]
79. Staudinger, J.; Roberts, P.V. A critical compilation of Henry's law constant temperature dependence relations for organic compounds in dilute aqueous solutions. *Chemosphere* **2001**, *44*, 561–576. [CrossRef] [PubMed]
80. Brusseau, M.L.; Van Glubt, S. The influence of surfactant and solution composition on PFAS adsorption at fluid-fluid interfaces. *Water Res.* **2019**, *161*, 17–26. [CrossRef]
81. Freire, M.G.; Carvalho, P.J.; Queimada, A.J.; Marrucho, I.M.; Coutinho, J.A.P. Surface tension of liquid fluorocompounds. *J. Chem. Eng. Data* **2006**, *51*, 1820–1824. [CrossRef]
82. Dong, D.; Kancharla, S.; Hooper, J.; Tsianou, M.; Bedrov, D.; Alexandridis, P. Controlling the self-assembly of perfluorinated surfactants in aqueous environments. *Phys. Chem. Chem. Phys.* **2021**, *23*, 10029–10039. [CrossRef]
83. Ng, C.A.; Hungerbühler, K. Bioconcentration of perfluorinated alkyl acids: How important is specific binding? *Environ. Sci. Technol.* **2013**, *47*, 7214–7223. [CrossRef]
84. Müller, C.E.; Lefevre, G.H.; Timofee, A.E.; Hussain, F.A.; Sattely, E.S.; Luthy, R.G. Competing mechanisms for perfluoroalkyl acid accumulation in plants revealed using an Arabidopsis model system. *Environ. Toxicol. Chem.* **2016**, *35*, 1138–1147. [CrossRef]
85. Droge, S.T.J. Membrane-water partition coefficients to aid risk assessment of perfluoroalkyl anions and alkyl sulfates. *Environ. Sci. Technol.* **2019**, *53*, 760–770. [CrossRef] [PubMed]
86. Vierke, L.; Berger, U.; Cousins, I.T. Estimation of the acid dissociation constant of perfluoroalkyl carboxylic acids through an experimental investigation of their water-to-air transport. *Environ. Sci. Technol.* **2013**, *47*, 11032–11039. [CrossRef]
87. Nguyen, T.M.H.; Bräunig, J.; Thompson, K.; Thompson, J.; Kabiri, S.; Navarro, D.A.; Kookana, R.S.; Grimson, C.; Barnes, C.M.; Higgins, C.P.; et al. Influences of chemical properties, soil properties, and solution pH on soil–water partitioning coefficients of per-and polyfluoroalkyl substances (PFASs). *Environ. Sci. Technol.* **2020**, *54*, 15883–15892. [CrossRef] [PubMed]
88. Meegoda, J.N.; Kewalramani, J.A.; Li, B.; Marsh, R.W. A review of the applications, environmental release, and remediation technologies of per- and polyfluoroalkyl substances. *Int. J. Environ. Res. Public Health* **2020**, *17*, 8117. [CrossRef]
89. Lang, J.R.; Allred, B.M.; Field, J.A.; Levis, J.W.; Barlaz, M.A. National Estimate of Per- and Polyfluoroalkyl Substance (PFAS) Release to U.S. Municipal Landfill Leachate. *Environ. Sci. Technol.* **2017**, *51*, 2197–2205. [CrossRef]
90. Sunderland, E.M.; Hu, X.C.; Dassuncao, C.; Tokranov, A.K.; Wagner, C.C.; Allen, J.G. A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. *J. Expo. Sci. Environ. Epidemiol.* **2019**, *29*, 131–147. [CrossRef]
91. Wang, Z.; Cousins, I.T.; Scheringer, M.; Buck, R.C.; Hungerbühler, K. Global emission inventories for C4–C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, Part I: Production and emissions from quantifiable sources. *Environ. Int.* **2014**, *70*, 62–75. [CrossRef]
92. Wang, Z.; Cousins, I.T.; Scheringer, M.; Buck, R.C.; Hungerbühler, K. Global emission inventories for C4–C14 perfluoroalkyl carboxylic acid (PFCA) homologues from 1951 to 2030, part II: The remaining pieces of the puzzle. *Environ. Int.* **2014**, *69*, 166–176. [CrossRef] [PubMed]
93. Brunn, H.; Arnold, G.; Körner, W.; Rippen, G.; Steinhäuser, K.G.; Valentin, I. PFAS: Forever chemicals—Persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites. *Environ. Sci. Eur.* **2023**, *35*, 20. [CrossRef]
94. Siegel, H.G.; Nason, S.L.; Warren, J.L.; Prunas, O.; Deziel, N.C.; Saiers, J.E. Investigation of Sources of Fluorinated Compounds in Private Water Supplies in an Oil and Gas-Producing Region of Northern West Virginia. *Environ. Sci. Technol.* **2023**, *57*, 17452–17464. [CrossRef]
95. Liu, D.L.; Nazaroff, W.W. Particle Penetration Through Building Cracks. *Aerosol Sci. Technol.* **2003**, *37*, 565–573. [CrossRef]
96. Armitage, J.M.; MacLeod, M.; Cousins, I.T. Modeling the Global Fate and Transport of Perfluorooctanoic Acid (PFOA) and Perfluorooctanoate (PFO) Emitted from Direct Sources Using a Multispecies Mass Balance Model. *Environ. Sci. Technol.* **2009**, *43*, 1134–1140. [CrossRef] [PubMed]
97. Thackray, C.P.; Selin, N.E.; Young, C.J. A global atmospheric chemistry model for the fate and transport of PFCAs and their precursors. *Environ. Sci. Process. Impacts* **2020**, *22*, 285–293. [CrossRef] [PubMed]
98. MacInnis, J.J.; Lehnherr, I.; Muir, D.C.G.; St. Pierre, K.A.; St. Louis, V.L.; Spencer, C.; De Silva, A.O. Fate and Transport of Perfluoroalkyl Substances from Snowpacks into a Lake in the High Arctic of Canada. *Environ. Sci. Technol.* **2019**, *53*, 10753–10762. [CrossRef] [PubMed]
99. Casas, G.; Martínez-Varela, A.; Roscales, J.L.; Vila-Costa, M.; Dachs, J.; Jiménez, B. Enrichment of perfluoroalkyl substances in the sea-surface microlayer and sea-spray aerosols in the Southern Ocean. *Environ. Pollut.* **2020**, *267*, 115512. [CrossRef]
100. Faust, J.A. PFAS on atmospheric aerosol particles: A review. In *Environmental Science: Processes and Impacts 2022*; Royal Society of Chemistry: London, UK, 2022; Volume 25, Issue 2; pp. 133–150. [CrossRef]

101. Ellis, D.A.; Martin, J.W.; De Silva, A.O.; Mabury, S.A.; Hurley, M.D.; Sulbaek Andersen, M.P.; Wallington, T.J. Degradation of Fluorotelomer Alcohols: A Likely Atmospheric Source of Perfluorinated Carboxylic Acids. *Environ. Sci. Technol.* **2004**, *38*, 3316–3321. [CrossRef]
102. Tian, Y.; Yao, Y.; Chang, S.; Zhao, Z.; Zhao, Y.; Yuan, X.; Wu, F.; Sun, H. Occurrence and Phase Distribution of Neutral and Ionizable Per- and Polyfluoroalkyl Substances (PFASs) in the Atmosphere and Plant Leaves around Landfills: A Case Study in Tianjin, China. *Environ. Sci. Technol.* **2018**, *52*, 1301–1310. [CrossRef]
103. Yao, Y.; Chang, S.; Sun, H.; Gan, Z.; Hu, H.; Zhao, Y.; Zhang, Y. Neutral and ionic per- and polyfluoroalkyl substances (PFASs) in atmospheric and dry deposition samples over a source region (Tianjin, China). *Environ. Pollut.* **2016**, *212*, 449–456. [CrossRef]
104. Zhang, Q.; Jimenez, J.L.; Canagaratna, M.R.; Allan, J.D.; Coe, H.; Ulbrich, I.; Alfarra, M.R.; Takami, A.; Middlebrook, A.M.; Sun, Y.L.; et al. Ubiquity and dominance of oxygenated species in organic aerosols in anthropogenically-influenced Northern Hemisphere midlatitudes. *Geophys. Res. Lett.* **2007**, *34*, L13801. [CrossRef]
105. Riemer, N.; Ault, A.P.; West, M.; Craig, R.L.; Curtis, J.H. Aerosol Mixing State: Measurements, Modeling, and Impacts. *Rev. Geophys.* **2019**, *57*, 187–249. [CrossRef]
106. Intergovernmental Panel on Climate Change (IPCC). Short-lived Climate Forcers. In *Climate Change 2021—The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2023; pp. 817–922. [CrossRef]
107. Intergovernmental Panel on Climate Change (IPCC). The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. In *Climate Change 2021—The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2023; pp. 923–1054. [CrossRef]
108. Schwidetzky, R.; Sun, Y.; Fröhlich-Nowoisky, J.; Kunert, A.T.; Bonn, M.; Meister, K. Ice Nucleation Activity of Perfluorinated Organic Acids. *J. Phys. Chem. Lett.* **2021**, *12*, 3431–3435. [CrossRef]
109. Alam, M.J.; Karim, I.; Zaman, S.U. Seasonal dynamics and trends in air pollutants: A comprehensive analysis of PM2.5, NO_2, CO, SO_2 and O_3 in Houston, USA. *Air Qual. Atmos. Health* **2025**, *18*, 2625–2642. [CrossRef]
110. Alam, M.J.; Rappenglueck, B.; Retama, A.H.; Rivera-Hernández, O. Investigating the Complexities of VOC Sources in Mexico City in the Years 2016–2022. *Atmosphere* **2024**, *15*, 179. [CrossRef]
111. Karim, I.; Rappenglück, B. Impact of COVID-19 lockdown regulations on PM2.5 and trace gases (NO_2, SO_2, CH_4, HCHO, $C_2H_2O_2$ and O_3) over Lahore, Pakistan. *Atmos. Environ.* **2023**, *303*, 119746. [CrossRef]
112. Wang, C.; Collins, D.B.; Arata, C.; Goldstein, A.H.; Mattila, J.M.; Farmer, D.K.; Ampollini, L.; DeCarlo, P.F.; Novoselac, A.; Vance, M.E.; et al. Surface reservoirs dominate dynamic gas-surface partitioning of many indoor air constituents. *Sci. Adv.* **2020**, *6*, eaay8973. [CrossRef]
113. Chang, M.C.; Chung, S.M.; Kwak, S.G. Exposure to perfluoroalkyl and polyfluoroalkyl substances and risk of stroke in adults: A meta-analysis. *Rev. Environ. Health* **2024**, *39*, 791–800. [CrossRef]
114. Ahrens, L.; Harner, T.; Shoeib, M.; Koblizkova, M.; Reiner, E.J. Characterization of Two Passive Air Samplers for Per- and Polyfluoroalkyl Substances. *Environ. Sci. Technol.* **2013**, *47*, 14024–14033. [CrossRef] [PubMed]
115. Ahrens, L.; Shoeib, M.; Harner, T.; Lee, S.C.; Guo, R.; Reiner, E.J. Wastewater Treatment Plant and Landfills as Sources of Polyfluoroalkyl Compounds to the Atmosphere. *Environ. Sci. Technol.* **2011**, *45*, 8098–8105. [CrossRef] [PubMed]
116. Naile, J.E.; Khim, J.S.; Hong, S.; Park, J.; Kwon, B.-O.; Ryu, J.S.; Hwang, J.H.; Jones, P.D.; Giesy, J.P. Distributions and bioconcentration characteristics of perfluorinated compounds in environmental samples collected from the west coast of Korea. *Chemosphere* **2013**, *90*, 387–394. [CrossRef]
117. Naile, J.E.; Khim, J.S.; Wang, T.; Chen, C.; Luo, W.; Kwon, B.-O.; Park, J.; Koh, C.-H.; Jones, P.D.; Lu, Y. Perfluorinated compounds in water, sediment, soil and biota from estuarine and coastal areas of Korea. *Environ. Pollut.* **2010**, *158*, 1237–1244. [CrossRef]
118. Pan, Y.; Shi, Y.; Wang, J.; Jin, X.; Cai, Y. Pilot investigation of perfluorinated compounds in river water, sediment, soil, and fish in Tianjin, China. *Bull. Environ. Contam. Toxicol.* **2011**, *87*, 152–157. [CrossRef]
119. Scher, D.P.; Kelly, J.E.; Huset, C.A.; Barry, K.M.; Hoffbeck, R.W.; Yingling, V.L.; Messing, R.B. Occurrence of perfluoroalkyl substances (PFAS) in garden produce at homes with a history of PFAS-contaminated drinking water. *Chemosphere* **2018**, *196*, 548–555. [CrossRef]
120. Zhu, H.; Kannan, K. Distribution and partitioning of perfluoroalkyl carboxylic acids in surface soil, plants, and earthworms at a contaminated site. *Sci. Total Environ.* **2019**, *647*, 954–961. [CrossRef] [PubMed]
121. Sorengard, M.; Kikuchi, J.; Wiberg, K.; Lutz, A. Spatial distribution and load of per- and polyfluoroalkyl substances (PFASs) in background soils in Sweden. *Chemosphere* **2022**, *295*, 133944. [CrossRef]
122. Braunig, J.; Baduel, C.; Heffernan, A.; Rotander, A.; Donaldson, E.; Mueller, J.F. Fate and redistribution of perfluoroalkyl acids through AFFF-impacted groundwater. *Sci. Total Environ.* **2017**, *596*, 360–368. [CrossRef] [PubMed]
123. Paul, A.G.; Jones, K.C.; Sweetman, A.J. A First Global Production, Emission, and Environmental Inventory for Perfluorooctane Sulfonate. *Environ. Sci. Technol.* **2009**, *43*, 386–392. [CrossRef] [PubMed]
124. Huset, C.A.; Chiaia, A.C.; Barofsky, D.F.; Jonkers, N.; Kohler, H.-P.E.; Ort, C.; Giger, W.; Field, J.A. Occurrence and Mass Flows of Fluorochemicals in the Glatt Valley Watershed, Switzerland. *Environ. Sci. Technol.* **2008**, *42*, 6369–6377. [CrossRef]

125. Möller, A.; Ahrens, L.; Surm, R.; Westerveld, J.; van der Wielen, F.; Ebinghaus, R.; de Voogt, P. Distribution and sources of polyfluoroalkyl substances (PFAS) in the River Rhine watershed. *Environ. Pollut.* **2010**, *158*, 3243–3250. [CrossRef]
126. Schultz, M.M.; Higgins, C.P.; Huset, C.A.; Luthy, R.G.; Barofsky, D.F.; Field, J.A. Fluorochemical Mass Flows in a Municipal Wastewater Treatment Facility. *Environ. Sci. Technol.* **2006**, *40*, 7350–7357. [CrossRef]
127. Ackerman Grunfeld, D.; Gilbert, D.; Hou, J.; Jones, A.M.; Lee, M.J.; Kibbey, T.C.; O'Carroll, D.M. Underestimated burden of per-and polyfluoroalkyl substances in global surface waters and groundwaters. *Nat. Geosci.* **2024**, *17*, 340–346. [CrossRef]
128. Benaafi, M.; Bafaqeer, A. Comprehensive Review of Global Perspectives on Per- and Polyfluoroalkyl Compounds: Occurrence, Fate, and Remediation in Groundwater Systems. *Water* **2024**, *16*, 1583. [CrossRef]
129. Koulini, G.; Nambi, I. Occurrence of forever chemicals in Chennai waters, India. *Environ. Sci. Eur.* **2024**, *36*, 60. [CrossRef]
130. Kurwadkar, S.; Dane, J.; Kanel, S.; Nadagouda, M.; Cawdrey, R.; Ambade, B.; Struckhoff, G.; Wilkin, R. Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution. *Sci. Total Environ.* **2021**, *809*, 151003. [CrossRef]
131. Sepulvado, J.G.; Blaine, A.C.; Hundal, L.S.; Higgins, C.P. Occurrence and Fate of Perfluorochemicals in Soil Following the Land Application of Municipal Biosolids. *Environ. Sci. Technol.* **2011**, *45*, 8106–8112. [CrossRef] [PubMed]
132. Pan, Y.; Zhang, H.; Cui, Q.; Sheng, N.; Yeung, L.W.Y.; Sun, Y.; Guo, Y.; Dai, J. Worldwide Distribution of Novel Perfluoroether Carboxylic and Sulfonic Acids in Surface Water. *Environ. Sci. Technol.* **2018**, *52*, 7621–7629. [CrossRef] [PubMed]
133. Kaboré, H.A.; Vo Duy, S.; Munoz, G.; Méité, L.; Desrosiers, M.; Liu, J.; Sory, T.K.; Sauvé, S. Worldwide drinking water occurrence and levels of newly-identified perfluoroalkyl and polyfluoroalkyl substances. *Sci. Total Environ.* **2018**, *616–617*, 1089–1100. [CrossRef]
134. Yeung, L.W.Y.; Dassuncao, C.; Mabury, S.; Sunderland, E.M.; Zhang, X.; Lohmann, R. Vertical Profiles, Sources, and Transport of PFASs in the Arctic Ocean. *Environ. Sci. Technol.* **2017**, *51*, 6735–6744. [CrossRef]
135. Bartell, S.M.; Calafat, A.M.; Lyu, C.; Kato, K.; Ryan, P.B.; Steenland, K. Rate of decline in serum PFOA concentrations after granular activated carbon filtration at two public water systems in Ohio and West Virginia. *Environ. Health Perspect.* **2010**, *118*, 222–228. [CrossRef] [PubMed]
136. Frisbee, S.J.; Brooks, A.P., Jr.; Maher, A.; Flensborg, P.; Arnold, S.; Fletcher, T.; Steenland, K.; Shankar, A.; Knox, S.S.; Pollard, C.; et al. The C8 health project: Design, methods, and participants. *Environ. Health Perspect.* **2009**, *117*, 1873–1882. [CrossRef]
137. D'eon, J.C.; Crozier, P.W.; Furdui, V.I.; Reiner, E.J.; Libelo, E.L.; Mabury, S.A. Perfluorinated phosphonic acids in Canadian surface waters and wastewater treatment plant effluent: Discovery of a new class of perfluorinated acids. *Environ. Toxicol. Chem.* **2009**, *28*, 2101–2107. [CrossRef]
138. Skutlarek, D.; Exner, M.; Färber, H. Perfluorinated surfactants in surface and drinking waters. *Environ. Sci. Pollut. Res. Int.* **2006**, *13*, 299–307.
139. Boiteux, V.; Dauchy, X.; Rosin, C.; Munoz, J.F. National screening study on 10 perfluorinated compounds in raw and treated tap water in France. *Arch. Environ. Contam. Toxicol.* **2012**, *63*, 1–12. [CrossRef] [PubMed]
140. Thompson, J.; Eaglesham, G.; Mueller, J. Concentrations of PFOS, PFOA and other perfluorinated alkyl acids in Australian drinking water. *Chemosphere* **2011**, *83*, 1320–1325. [CrossRef]
141. Takagi, S.; Adachi, F.; Miyano, K.; Koizumi, Y.; Tanaka, H.; Watanabe, I.; Tanabe, S.; Kannan, K. Fate of Perfluorooctanesulfonate and perfluorooctanoate in drinking water treatment processes. *Water Res.* **2011**, *45*, 3925–3932. [CrossRef]
142. Kim, D.H.; Lee, J.H.; Oh, J.E. Assessment of individual-based perfluoroalkly substances exposure by multiple human exposure sources. *J. Hazard Mater.* **2019**, *365*, 26–33. [CrossRef]
143. Tan, K.Y.; Lu, G.H.; Piao, H.T.; Chen, S.; Jiao, X.C.; Gai, N.; Yamazaki, E.; Yamashita, N.; Pan, J.; Yang, Y.L. Current contamination status of perfluoroalkyl substances in tapwater from 17 cities in the Eastern China and their correlations with surface waters. *Bull. Environ. Contam. Toxicol.* **2017**, *99*, 224–231. [CrossRef]
144. Sharma, B.M.; Bharat, G.K.; Tayal, S.; Larssen, T.; Bečanová, J.; Karásková, P.; Whitehead, P.G.; Futter, M.N.; Butterfield, D.; Nizzetto, L. Perfluoroalkyl substances (PFAS) in river and ground/drinking water of the Ganges River basin: Emissions and implications for human exposure. *Environ. Pollut.* **2016**, *208 Pt B*, 704–713. [CrossRef]
145. Hemat, H.; Wilhelm, M.; Völkel, W.; Mosch, C.; Fromme, H.; Wittsiepe, J. Low serum levels of perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS) and perfluorohexane sulfonate (PFHxS) in children and adults from Afghanistan. *Sci. Total Environ.* **2010**, *408*, 3493–3495. [CrossRef]
146. Essumang, D.K.; Eshun, A.; Hogarh, J.N.; Bentum, J.K.; Adjei, J.K.; Negishi, J.; Nakamichi, S.; Habibullah-Al-Mamun, M.; Masunaga, S. Perfluoroalkyl acids (PFAAs) in the Pra and Kakum River basins and associated tap water in Ghana. *Sci. Total Environ.* **2017**, *579*, 729–735. [CrossRef]
147. Lin, H.; Taniyasu, S.; Yamazaki, E.; Wei, S.; Wang, X.; Gai, N.; Kim, J.H.; Eun, H.; Lam, P.K.S.; Yamashita, N. Per- and Polyfluoroalkyl Substances in the Air Particles of Asia: Levels, Seasonality, and Size-Dependent Distribution. *Environ. Sci. Technol.* **2020**, *54*, 14182–14191. [CrossRef] [PubMed]

148. Shimizu, M.S.; Mott, R.; Potter, A.; Zhou, J.; Baumann, K.; Surratt, J.D.; Turpin, B.; Avery, G.B.; Harfmann, J.; Kieber, R.J.; et al. Atmospheric Deposition and Annual Flux of Legacy Perfluoroalkyl Substances and Replacement Perfluoroalkyl Ether Carboxylic Acids in Wilmington, NC, USA. *Environ. Sci. Technol. Lett.* **2021**, *8*, 366–372. [CrossRef]
149. Chen, H.; Zhang, L.; Li, M.; Yao, Y.; Zhao, Z.; Munoz, G.; Sun, H. Per- and polyfluoroalkyl substances (PFASs) in precipitation from mainland China: Contributions of unknown precursors and short-chain (C2 C3) perfluoroalkyl carboxylic acids. *Water Res.* **2019**, *153*, 169–177. [CrossRef]
150. Gewurtz, S.B.; Bradley, L.E.; Backus, S.; Dove, A.; McGoldrick, D.; Hung, H.; Dryfhout-Clark, H. Perfluoroalkyl Acids in Great Lakes Precipitation and Surface Water (2006–2018) Indicate Response to Phase-outs, Regulatory Action, and Variability in Fate and Transport Processes. *Environ. Sci. Technol.* **2019**, *53*, 8543–8552. [CrossRef] [PubMed]
151. Webster, E.M.; Ellis, D.A. Understanding the atmospheric measurement and behavior of perfluorooctanoic acid. *Environ. Toxicol. Chem.* **2012**, *31*, 2041–2046. [CrossRef]
152. Young, C.J.; Furdui, V.I.; Franklin, J.; Koerner, R.M.; Muir, D.C.G.; Mabury, S.A. Perfluorinated Acids in Arctic Snow: New Evidence for Atmospheric Formation. *Environ. Sci. Technol.* **2007**, *41*, 3455–3461. [CrossRef]
153. Gauthier, S.A.; Mabury, S.A. Aqueous photolysis of 8:2 fluorotelomer alcohol. *Environ. Toxicol. Chem.* **2005**, *24*, 1837–1846. [CrossRef]
154. Borthakur, A.; Leonard, J.; Koutnik, V.S.; Ravi, S.; Mohanty, S.K. Inhalation risks of wind-blown dust from biosolid-applied agricultural lands: Are they enriched with microplastics and PFAS? *Curr. Opin. Environ. Sci. Health* **2022**, *25*, 100309. [CrossRef]
155. Adamson, D.T.; Kulkarni, P.R.; Nickerson, A.; Higgins, C.P.; Field, J.; Schwichtenberg, T.; Newell, C.; Kornuc, J.J. Characterization of relevant site-specific PFAS fate and transport processes at multiple AFFF sites. *Environ. Adv.* **2022**, *7*, 100167. [CrossRef]
156. Groffen, T.; Eens, M.; Bervoets, L. Do concentrations of perfluoroalkylated acids (PFAAs) in isopods reflect concentrations in soil and songbirds? A study using a distance gradient from a fluorochemical plant. *Sci. Total Environ.* **2019**, *657*, 111–123. [CrossRef]
157. Pepper, I.L.; Brusseau, M.L.; Prevatt, F.J.; Escobar, B.A. Incidence of Pfas in soil following long-term application of class B biosolids. *Sci. Total Environ.* **2021**, *793*, 148449. [CrossRef]
158. Johnson, G.R. PFAS in soil and groundwater following historical land application of biosolids. *Water Res.* **2022**, *211*, 118035. [CrossRef] [PubMed]
159. Loganathan, N.; Wilson, A.K. Adsorption, Structure, and Dynamics of Short- and Long-Chain PFAS Molecules in Kaolinite: Molecular-Level Insights. *Environ. Sci. Technol.* **2022**, *56*, 8043–8052. [CrossRef]
160. Xu, B.; Yang, G.; Lehmann, A.; Riedel, S.; Rillig, M.C. Effects of perfluoroalkyl and polyfluoroalkyl substances (PFAS) on soil structure and function. *Soil Ecol. Lett.* **2023**, *5*, 108–117. [CrossRef]
161. Qiao, W.; Xie, Z.; Zhang, Y.; Liu, X.; Xie, S.; Huang, J.; Yu, L. Perfluoroalkyl substances (PFASs) influence the structure and function of soil bacterial community: Greenhouse experiment. *Sci. Total Environ.* **2018**, *642*, 1118–1126. [CrossRef]
162. Biesek, B.; Szymkiewicz, A.; Šimůnek, J.; Gumula-Kawecka, A.; Jaworska-Szulc, B. Numerical modeling of PFAS movement through the vadose zone: Influence of plant water uptake and soil organic carbon distribution. *Sci. Total Environ.* **2024**, *935*, 173252. [CrossRef]
163. Mei, W.; Sun, H.; Song, M.; Jiang, L.; Li, Y.; Lu, W.; Ying, G.; Luo, C.; Zhang, G. Per- and polyfluoroalkyl substances (PFASs) in the soil-plant system: Sorption, root uptake, and translocation. *Environ. Int.* **2021**, *156*, 106642. [CrossRef]
164. Zhang, W.; Cao, H.; Liang, Y. Plant uptake and soil fractionation of five ether-PFAS in plant-soil systems. *Sci. Total Environ.* **2021**, *771*, 144805. [CrossRef] [PubMed]
165. Xu, B.; Qiu, W.; Du, J.; Wan, Z.; Zhou, J.; Chen, H.; Liu, R.; Magnuson, J.; Zheng, C. Translocation, bioaccumulation, and distribution of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in plants. *iScience* **2022**, *25*, 104061. [CrossRef]
166. Biek, S.; Khudur, L.; Rigby, L.; Singh, N.; Askeland, M.; Ball, A. Assessing the impact of immobilisation on the bioavailability of PFAS to plants in contaminated Australian soils. *Environ. Sci. Pollut. Res. Int.* **2024**, *31*, 20330–20342. [CrossRef]
167. Hearon, S.; Orr, A.; Moyer, H.; Wang, M.; Tamamis, P.; Phillips, T. Montmorillonite clay-based sorbents decrease the bioavailability of per- and polyfluoroalkyl substances (PFAS) from soil and their translocation to plants. *Environ. Res.* **2021**, *205*, 112433. [CrossRef]
168. Cai, W.; Navarro, D.; Du, J.; Ying, G.; Yang, B.; Mclaughlin, M.; Kookana, R. Increasing ionic strength and valency of cations enhance sorption through hydrophobic interactions of PFAS with soil surfaces. *Sci. Total Environ.* **2022**, *817*, 152975. [CrossRef] [PubMed]
169. McGarr, J.; Mbonimpa, E.; McAvoy, D.; Soltanian, M. Fate and Transport of Per- and Polyfluoroalkyl Substances (PFAS) at Aqueous Film Forming Foam (AFFF) Discharge Sites: A Review. *Soil Syst.* **2023**, *7*, 53. [CrossRef]
170. Brusseau, M.; Anderson, H.; Guo, B. PFAS concentrations in soils: Background levels versus contaminated sites. *Sci. Total Environ.* **2020**, *740*, 140017. [CrossRef]
171. Panieri, E.; Baralić, K.; Djukic-Cosic, D.; Djordjevic, A.; Saso, L. PFAS Molecules: A Major Concern for the Human Health and the Environment. *Toxics* **2022**, *10*, 44. [CrossRef]

172. Lemay, A.; Bourg, I. Interactions between Per- and Polyfluoroalkyl Substances (PFAS) at the Water-Air Interface. *Environ. Sci. Technol.* **2025**, *59*, 2201–2210. [CrossRef]
173. Qi, Y.; Cao, H.; Pan, W.; Wang, C.; Liang, Y. The role of dissolved organic matter during Per- and Polyfluorinated Substance (PFAS) adsorption, degradation, and plant uptake: A review. *J. Hazard. Mater.* **2022**, *436*, 129139. [CrossRef] [PubMed]
174. Weschler, C.J.; Nazaroff, W.W. Semivolatile organic compounds in indoor environments. *Atmos Environ.* **2008**, *42*, 9018–9040. [CrossRef]
175. Letcher, R.J.; Chu, S.G.; Smyth, S.A. Side-chain fluorinated polymer surfactants in biosolids from wastewater treatment plants. *J. Hazard Mater.* **2020**, *388*, 122044. [CrossRef] [PubMed]
176. Shoeib, M.; Harner, T.; Wilford, B.H.; Jones, K.C.; Zhu, J. Perfluorinated sulfonamides in indoor and outdoor air and indoor dust: Occurrence, partitioning, and human exposure. *Environ. Sci. Technol.* **2005**, *39*, 6599–6606. [CrossRef]
177. Trowbridge, J.; Gerona, R.R.; Lin, T.; Rudel, R.A.; Bessonneau, V.; Buren, H.; Morello-Frosch, R. Exposure to perfluoroalkyl substances in a cohort of women firefighters and office workers in San Francisco. *Environ. Sci. Technol.* **2020**, *54*, 3363–3374. [CrossRef]
178. Mogensen, U.; Grandjean, P.; Nielsen, F.; Weihe, P.; Budtz-Jorgensen, E. Breastfeeding as an exposure pathway for perfluorinated alkylates. *Environ. Sci. Technol.* **2015**, *49*, 10466–10473. [CrossRef]
179. Poothong, S.; Papadopoulou, E.; Padilla-Sanchez, J.A.; Thomsen, C.; Haug, L.S. Multiple pathways of human exposure to poly- and perfluoroalkyl substances (PFASs): From external exposure to human blood. *Environ. Int.* **2020**, *134*, 105244. [CrossRef]
180. Martin, J.W.; Muir, D.C.G.; Moody, C.A.; Ellis, D.A.; Wai, C.K.; Solomon, K.R.; Mabury, S.A. Collection of airborne fluorinated organics and analysis by gas chromatography/chemical ionization mass spectrometry. *Anal. Chem.* **2002**, *74*, 584–590. [CrossRef]
181. Guo, M.; Lyu, Y.; Xu, T.; Yao, B.; Song, W.; Li, M.; Yang, X.; Cheng, T.; Li, X. Particle size distribution and respiratory deposition estimates of airborne perfluoroalkyl acids during the haze period in the megacity of Shanghai. *Environ. Pollut.* **2018**, *234*, 9–19. [CrossRef]
182. Makey, C.M.; Webster, T.F.; Martin, J.W.; Shoeib, M.; Harner, T.; Dix-Cooper, L.; Webster, G.M. Airborne precursors predict maternal serum perfluoroalkyl acid concentrations. *Environ. Sci. Technol.* **2017**, *51*, 7667–7675. [CrossRef]
183. Goosey, E.; Harrad, S. Perfluoroalkyl substances in UK indoor and outdoor air: Spatial and seasonal variation, and implications for human exposure. *Environ. Int.* **2012**, *45*, 86–90. [CrossRef] [PubMed]
184. Zheng, G.M.; Boor, B.E.; Schreder, E.; Salamova, A. Indoor exposure to per- and polyfluoroalkyl substances (PFAS) in the childcare environment. *Environ. Pollut.* **2020**, *258*, 113714. [CrossRef]
185. Gerbersdorf, S.U.; Wieprecht, S. Biostabilization of cohesive sediments: Revisiting the role of abiotic conditions, physiology and diversity of microbes, polymeric secretion, and biofilm architecture. *Geobiology* **2015**, *13*, 68–97. [CrossRef]
186. Munoz, G.; Fechner, L.C.; Geneste, E.; Pardon, P.; Budzinski, H.; Labadie, P. Spatiotemporal dynamics of per and polyfluoroalkyl substances (PFASs) and transfer to periphytic biofilm in an urban river: Case-study on the River Seine. *Environ. Sci. Pollut. Res.* **2018**, *25*, 23574–23582. [CrossRef] [PubMed]
187. Fitzgerald, N.J.M.; Wargenau, A.; Sorenson, C.; Pedersen, J.; Tufenkji, N.; Novak, P.J.; Simcik, M.F. Partitioning and accumulation of perfluoroalkyl substances in model lipid bilayers and bacteria. *Environ. Sci. Technol.* **2018**, *52*, 10433–10440. [CrossRef]
188. Penland, T.N.; Cope, W.G.; Kwak, T.J.; Strynar, M.J.; Grieshaber, C.A.; Heise, R.J.; Sessions, F.W. Trophodynamics of per- and polyfluoroalkyl substances in the food web of a large Atlantic Slope River. *Environ. Sci. Technol.* **2020**, *54*, 6800–6811. [CrossRef] [PubMed]
189. Pi, N.; Ng, J.; Kelly, B. Uptake and elimination kinetics of perfluoroalkyl substances in submerged and free-floating aquatic macrophytes: Results of mesocosm experiments with Echinodorus horemanii and Eichhornia crassipes. *Water Res.* **2017**, *117*, 167–174. [CrossRef]
190. Ahrens, L.; Norström, K.; Viktor, T.; Cousins, A.P.; Josefsson, S. Stockholm Arlanda Airport as a source of per-and polyfluoroalkyl substances to water, sediment and fish. *Chemosphere* **2015**, *129*, 33–38.
191. Liu, J.; Zhao, X.; Liu, Y.; Qiao, X.; Wang, X.; Ma, M.; Jin, X.; Liu, C.; Zheng, B.; Shen, J.; et al. High contamination, bioaccumulation and risk assessment of perfluoroalkyl substances in multiple environmental media at the Baiyangdian Lake. *Ecotoxicol. Environ. Saf.* **2019**, *182*, 109454. [CrossRef]
192. Wen, W.; Xia, X.; Hu, D.; Zhou, D.; Wang, H.; Zhai, Y.; Lin, H. Long-chain perfluoroalkyl acids (PFAAs) affect the bioconcentration and tissue distribution of short-chain PFAAs in zebrafish (*Danio rerio*). *Environ. Sci. Technol.* **2017**, *51*, 12358–12368. [CrossRef]
193. Gazzotti, T.; Sirri, F.; Ghelli, E.; Zironi, E.; Zampiga, M.; Pagliuca, G. Perfluoroalkyl contaminants in eggs from backyard chickens reared in Italy. *Food Chem.* **2021**, *362*, 130178. [CrossRef] [PubMed]
194. EFSA Panel on Contaminants in the Food Chain (EFSA CONTAM Panel); Schrenk, D.; Bignami, M.; Bodin, L.; Chipman, J.K.; del Mazo, J.; Grasl-Kraupp, B.; Hogstrand, C.; Hoogenboom, L.; Leblanc, J.C.; et al. Risk to human health related to the presence of perfluoroalkyl substances in food. *EFSA J.* **2020**, *18*, e06223. [CrossRef]

195. Brown, J.B.; Conder, J.M.; Arblaster, J.A.; Higgins, C.P. Assessing human health risks from per- and polyfluoroalkyl substance (PFAS)-impacted vegetable consumption: A tiered modeling approach. *Environ. Sci. Technol.* **2020**, *54*, 15202–15214. [CrossRef] [PubMed]
196. Sadia, M.; Yeung, L.W.; Fiedler, H. Trace level analyses of selected perfluoroalkyl acids in food: Method development and data generation. *Environ. Pollut.* **2020**, *263*, 113721. [CrossRef] [PubMed]
197. Macheka, L.R.; Olowoyo, J.O.; Mugivhisa, L.L.; Abafe, O.A. Determination and assessment of human dietary intake of per- and polyfluoroalkyl substances in retail dairy milk and infant formula from South Africa. *Sci. Total Environ.* **2021**, *755*, 142697. [CrossRef]
198. Menzel, J.; Abraham, K.; Dietrich, S.; Fromme, H.; Voelkel, W.; Schwerdtle, T.; Weikert, C. Internal exposure to perfluoroalkyl substances (PFAS) in vegans and omnivores. *Int. J. Hyg. Environ. Health* **2021**, *237*, 113808. [CrossRef]
199. Sinclair, G.M.; Long, S.M.; Jones, O.A. What are the effects of PFAS exposure at environmentally relevant concentrations? *Chemosphere* **2020**, *258*, 127340. [CrossRef]
200. India-Aldana, S.; Yao, M.; Midya, V.; Colicino, E.; Chatzi, L.; Chu, J.; Gennings, C.; Jones, D.; Loos, R.; Setiawan, V.; et al. PFAS Exposures and the Human Metabolome: A Systematic Review of Epidemiological Studies. *Curr. Pollut. Rep.* **2023**, *9*, 510–568. [CrossRef]
201. Fenton, S.; Ducatman, A.; Boobis, A.; DeWitt, J.; Lau, C.; Ng, C.; Smith, J.; Roberts, S. Per- and Polyfluoroalkyl Substance Toxicity and Human Health Review: Current State of Knowledge and Strategies for Informing Future Research. *Environ. Toxicol. Chem.* **2020**, *40*, 606–630. [CrossRef]
202. Chen, Y.R.; Lin, S.B.; Lv, J.Y.; Wu, Y.; Feng, W.R. Dissect the association between per-and polyfluoroalkyl substances (PFAS) and kidney function from the perspective of lipid molecules. *Environ. Pollut.* **2024**, *361*, 124865. [CrossRef]
203. Yang, M.; Su, W.; Li, H.; Li, L.; An, Z.; Xiao, F.; Liu, Y.; Zhang, X.; Liu, X.; Guo, H.; et al. Association of per-and polyfluoroalkyl substances with hepatic steatosis and metabolic dysfunction-associated fatty liver disease among patients with acute coronary syndrome. *Ecotoxicol. Environ. Saf.* **2023**, *264*, 115473. [CrossRef] [PubMed]
204. Zhang, X.; Flaws, J.A.; Spinella, M.J.; Irudayaraj, J. The relationship between typical environmental endocrine disruptors and kidney disease. *Toxics* **2022**, *11*, 32. [CrossRef] [PubMed]
205. Qin, X.D.; Qian, Z.M.; Dharmage, S.C.; Perret, J.; Geiger, S.D.; Rigdon, S.E.; Howard, S.; Zeng, X.W.; Hu, L.W.; Yang, B.Y.; et al. Association of perfluoroalkyl substances exposure with impaired lung function in children. *Environ. Res.* **2017**, *155*, 15–21. [CrossRef]
206. Kvalem, H.E.; Nygaard, U.C.; Carlsen, K.L.; Carlsen, K.H.; Haug, L.S.; Granum, B. Perfluoroalkyl substances, airways infections, allergy and asthma related health outcomes–implications of gender, exposure period and study design. *Environ. Int.* **2020**, *134*, 105259. [CrossRef]
207. von Holst, H.; Nayak, P.; Dembek, Z.; Buehler, S.; Echeverria, D.; Fallacara, D.; John, L. Perfluoroalkyl substances exposure and immunity, allergic response, infection, and asthma in children: Review of epidemiologic studies. *Heliyon* **2021**, *7*, e08160. [CrossRef]
208. Nian, M.; Luo, K.; Luo, F.; Aimuzi, R.; Huo, X.; Chen, Q.; Tian, Y.; Zhang, J. Association between prenatal exposure to PFAS and fetal sex hormones: Are the short-chain PFAS safer? *Environ. Sci. Technol.* **2020**, *54*, 8291–8299. [CrossRef] [PubMed]
209. Gao, K.; Zhuang, T.; Liu, X.; Fu, J.; Zhang, J.; Fu, J.; Wang, L.; Zhang, A.; Liang, Y.; Song, M.; et al. Prenatal exposure to per-and polyfluoroalkyl substances (PFASs) and association between the placental transfer efficiencies and dissociation constant of serum proteins–PFAS complexes. *Environ. Sci. Technol.* **2019**, *53*, 6529–6538. [CrossRef]
210. Chen, Z.; Yang, T.; Walker, D.I.; Thomas, D.C.; Qiu, C.; Chatzi, L.; Alderete, T.L.; Kim, J.S.; Conti, D.V.; Breton, C.V.; et al. Dysregulated lipid and fatty acid metabolism link perfluoroalkyl substances exposure and impaired glucose metabolism in young adults. *Environ. Int.* **2020**, *145*, 106091. [CrossRef]
211. Yu, G.; Jin, M.; Huang, Y.; Aimuzi, R.; Zheng, T.; Nian, M.; Tian, Y.; Wang, W.; Luo, Z.; Shen, L.; et al. Environmental exposure to perfluoroalkyl substances in early pregnancy, maternal glucose homeostasis and the risk of gestational diabetes: A prospective cohort study. *Environ. Int.* **2021**, *156*, 106621. [CrossRef]
212. Halldorsson, T.I.; Rytter, D.; Haug, L.S.; Bech, B.H.; Danielsen, I.; Becher, G.; Henriksen, T.B.; Olsen, S.F. Prenatal exposure to perfluorooctanoate and risk of overweight at 20 years of age: A prospective cohort study. *Environ. Health Perspect.* **2012**, *120*, 668–673. [CrossRef]
213. Vieira, V.M.; Hoffman, K.; Shin, H.M.; Weinberg, J.M.; Webster, T.F.; Fletcher, T. Perfluorooctanoic acid exposure and cancer outcomes in a contaminated community: A geographic analysis. *Environ. Health Perspect.* **2013**, *121*, 318–323. [CrossRef]
214. Li, Y.; Fletcher, T.; Mucs, D.; Scott, K.; Lindh, C.H.; Tallving, P.; Jakobsson, K. Half-lives of PFOS, PFHxS and PFOA after end of exposure to contaminated drinking water. *Occup. Environ. Med.* **2018**, *75*, 46–51. [CrossRef]
215. Pitter, G.; Da Re, F.; Canova, C.; Barbieri, G.; Zare Jeddi, M.; Daprà, F.; Manea, F.; Zolin, R.; Bettega, A.M.; Stopazzolo, G.; et al. Serum levels of perfluoroalkyl substances (PFAS) in adolescents and young adults exposed to contaminated drinking water in the Veneto region, Italy: A cross-sectional study based on a health surveillance program. *Environ. Health Perspect.* **2020**, *128*, 027007. [CrossRef] [PubMed]

216. Zhang, L.; Liang, J.; Gao, A. Contact to perfluoroalkyl substances and thyroid health effects: A meta-analysis directing on pregnancy. *Chemosphere* **2023**, *315*, 137748. [CrossRef] [PubMed]
217. Fini, J.B.; Mughal, B.B.; Le Mével, S.; Leemans, M.; Lettmann, M.; Spirhanzlova, P.; Affaticati, P.; Jenett, A.; Demeneix, B.A. Human amniotic fluid contaminants alter thyroid hormone signalling and early brain development in Xenopus embryos. *Sci. Rep.* **2017**, *7*, 43786. [CrossRef]
218. Ghisi, R.; Vamerali, T.; Manzetti, S. Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: A review. *Environ. Res.* **2019**, *169*, 326–341. [CrossRef] [PubMed]
219. Pizzurro, D.M.; Seeley, M.; Kerper, L.E.; Beck, B.D. Interspecies differences in perfluoroalkyl substances (PFAS) toxicokinetics and application to health-based criteria. *Regul. Toxicol. Pharmacol.* **2019**, *106*, 239–250. [CrossRef] [PubMed]
220. Rafiee, A.; Faridi, S.; Sly, P.D.; Stone, L.; Kennedy, L.; Mahabee-Gittens, E.M. Asthma and Decreased Lung Function in Children Exposed to Perfluoroalkyl and Polyfluoroalkyl Substances (PFASs): An Updated Meta-Analysis Unveiling Research Gaps. *Environ. Res.* **2024**, *262*, 119827. [CrossRef]
221. Sebastiano, M.; Jouanneau, W.; Blévin, P.; Angelier, F.; Parenteau, C.; Gernigon, J.; Lemesle, J.C.; Robin, F.; Pardon, P.; Budzinski, H.; et al. High levels of fluoroalkyl substances and potential disruption of thyroid hormones in three gull species from South Western France. *Sci. Total Environ.* **2021**, *765*, 144611. [CrossRef] [PubMed]
222. Kvamme, S. Levels of Per- and Polyfluoroalkyl Substances (PFAS), Trace Elements, and Steroid Hormones in Arctic Char (*Salvelinus alpinus*) from Lake Diesetvatnet, Svalbard. Master's Thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2022.
223. Dunder, L.; Salihovic, S.; Elmståhl, S.; Lind, P.M.; Lind, L. Associations between per-and polyfluoroalkyl substances (PFAS) and diabetes in two population-based cohort studies from Sweden. *J. Expo. Sci. Environ. Epidemiol.* **2023**, *33*, 748–756. [CrossRef] [PubMed]
224. Haimbaugh, A.; Meyer, D.N.; Connell, M.L.; Blount-Pacheco, J.; Tolofari, D.; Gonzalez, G.; Banerjee, D.; Norton, J.; Miller, C.J.; Baker, T.R. Environmental Exposure to Per-and Polyfluorylalkyl Substances (PFASs) and Reproductive Outcomes in the General Population: A Systematic Review of Epidemiological Studies. *Int. J. Environ. Res. Public Health* **2024**, *21*, 1615. [CrossRef]
225. Brown-Leung, J.M.; Cannon, J.R. Neurotransmission targets of per-and polyfluoroalkyl substance neurotoxicity: Mechanisms and potential implications for adverse neurological outcomes. *Chem. Res. Toxicol.* **2022**, *35*, 1312–1333. [CrossRef]
226. Baradaran Mahdavi, S.; Zamani, S.; Riahi, R.; Taheri, E.; Vahdatpour, B.; Sharifianjazi, F.; Kelishadi, R. Exposure to environmental chemicals and human bone health; A systematic review and meta-analysis. *Expo. Health* **2024**, *16*, 861–883. [CrossRef]
227. Zhang, M.; Rifas-Shiman, S.L.; Aris, I.M.; Fleisch, A.F.; Lin, P.I.; Nichols, A.R.; Oken, E.; Hivert, M.F. Associations of Prenatal Per-and Polyfluoroalkyl Substance (PFAS) Exposures with Offspring Adiposity and Body Composition at 16–20 Years of Age: Project Viva. *Environ. Health Perspect.* **2023**, *131*, 127002. [CrossRef]
228. Schlezinger, J.J.; Gokce, N. Perfluoroalkyl/polyfluoroalkyl substances: Links to cardiovascular disease risk. *Circ. Res.* **2024**, *134*, 1136–1159. [CrossRef]
229. Conway, B.N.; Badders, A.N.; Costacou, T.; Arthur, J.M.; Innes, K.E. Perfluoroalkyl substances and kidney function in chronic kidney disease, anemia, and diabetes. *Diabetes Metab. Syndr. Obes. Targets Ther.* **2018**, *11*, 707–716. [CrossRef]
230. Chang, N.Y.; Eichler, C.M.A.; Amparo, D.E.; Zhou, J.; Baumann, K.; Cohen Hubal, E.A.; Surratt, J.D.; Morrison, G.C.; Turpin, B.J. Indoor air concentrations of PM2.5 quartz fiber filter-collected ionic PFAS and emissions to outdoor air: Findings from the IPA campaign. *Environ. Sci. Process. Impacts* **2024**, *27*, 1603–1618. [CrossRef] [PubMed]
231. Donat-Vargas, C.; Bergdahl, I.A.; Tornevi, A.; Wennberg, M.; Sommar, J.; Kiviranta, H.; Koponen, J.; Rolandsson, O.; Åkesson, A. Perfluoroalkyl substances and risk of type II diabetes: A prospective nested case-control study. *Environ. Int.* **2019**, *123*, 390–398. [CrossRef]
232. Qiao, W.; Li, J.; Luo, L.; Peng, W.; Wang, X.; Jin, R.; Li, J. Triglycerides mediate the relationships of per-and poly-fluoroalkyl substance (PFAS) exposure with nonalcoholic fatty liver disease (NAFLD) risk in US participants. *Ecotoxicol. Environ. Saf.* **2025**, *289*, 117436. [CrossRef]
233. Van Larebeke, N.; Koppen, G.; De Craemer, S.; Colles, A.; Bruckers, L.; Den Hond, E.; Govarts, E.; Morrens, B.; Schettgen, T.; Remy, S.; et al. Per-and polyfluoroalkyl substances (PFAS) and immune system-related diseases: Results from the Flemish Environment and Health Study (FLEHS) 2008–2014. *Environ. Sci. Eur.* **2023**, *35*, 28. [CrossRef]
234. Pesonen, M.; Vähäkangas, K. Involvement of per-and polyfluoroalkyl compounds in tumor development. *Arch. Toxicol.* **2024**, *98*, 1241–1252. [CrossRef]
235. Seyyedsalehi, M.S.; Boffetta, P. Per-and poly-fluoroalkyl substances (PFAS) exposure and risk of kidney, liver, and testicular cancers: A systematic review and meta-analysis. *Med. Lav.* **2023**, *114*, e2023040. [CrossRef]
236. Svoboda, L.K.; Ishikawa, T.; Dolinoy, D.C. Developmental toxicant exposures and sex-specific effects on epigenetic programming and cardiovascular health across generations. *Environ. Epigenetics* **2022**, *8*, dvac017. [CrossRef]
237. De Silva, A.; Armitage, J.; Bruton, T.; Dassuncao, C.; Heiger-Bernays, W.; Hu, X.; Kärrman, A.; Kelly, B.; Ng, C.; Robuck, A.; et al. PFAS Exposure Pathways for Humans and Wildlife: A Synthesis of Current Knowledge and Key Gaps in Understanding. *Environ. Toxicol. Chem.* **2020**, *40*, 631–657. [CrossRef]

238. Vendl, C.; Taylor, M.; Bräunig, J.; Ricolfi, L.; Ahmed, R.; Chin, M.; Gibson, M.; Hesselson, D.; Neely, G.; Lagisz, M.; et al. Profiling research on PFAS in wildlife: Systematic evidence map and bibliometric analysis. *Ecol. Solut. Evid.* **2024**, *5*, e12292. [CrossRef]
239. DeLuca, N.M.; Minucci, J.M.; Mullikin, A.; Slover, R.; Hubal, E.A.C. Human exposure pathways to poly-and perfluoroalkyl substances (PFAS) from indoor media: A systematic review. *Environ. Int.* **2022**, *162*, 107149. [CrossRef] [PubMed]
240. Fabrega-Palau, J.; Vidal, M.; Rigol, A. Modelling the sorption behaviour of perfluoroalkyl carboxylates and perfluoroalkane sulfonates in soils. *Sci. Total Environ.* **2021**, *801*, 149343. [CrossRef] [PubMed]
241. Minovic, J.; Lacorte, S.; Vidal, M.; Rigol, A. Sorption behaviour of perfluoroalkyl substances in soils. *Sci. Total Environ.* **2015**, *511*, 63–71. [CrossRef] [PubMed]
242. Podder, A.; Sadmani, A.A.; Reinhart, D.; Chang, N.-B.; Goel, R. Per and poly-fluoroalkyl substances (PFAS) as a contaminant of emerging concern in surface water: A transboundary review of their occurrences and toxicity effects. *J. Hazard. Mater.* **2021**, *419*, 126361. [CrossRef]
243. Torralba-Sanchez, T.L.; Di Toro, M.D.; Dmitrenko, O.; Murillo-gelvez, J.; Tratnyek, P.G. Modeling the Partitioning of Anionic Carboxylic and Perfluoroalkyl Carboxylic and Sulfonic Acids to Octanol and Membrane Lipid. *Environ. Toxicol. Chem.* **2023**, *42*, 2317–2328. [CrossRef] [PubMed]

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