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REVIEW ARTICLE

Understanding per- and polyfluoroalkyl substances (PFAS): Environmental persistence, health risks, and regulatory challenges

Akash Phillip
Department of Biotechnology, IIMT University, Meerut, India

ABSTRACT

Per- and polyfluoroalkyl substances (PFASs) have emerged as a persistent and pervasive class of synthetic chemicals, widely used in industrial and consumer applications for their unique water-, oil-, and stain-resistant properties. This comprehensive review synthesizes multidisciplinary research addressing the historical evolution, chemical properties, environmental fate, and contamination pathways of PFAS, alongside their significant human health and ecological impacts. Despite decades of application and subsequent phase-out of certain legacy PFAS compounds specifically, such as by naming perfluorooctanesulfonic acid and perfluorooctanoic acid, these "forever chemicals" continue to persist in the environment, bioaccumulate in wildlife, and pose complex health risks, including endocrine disruption, immunotoxicity, and carcinogenicity. This review also critically examines current regulatory frameworks and policy challenges at international and national levels, highlighting substantial gaps that persist between scientific findings and legal standards. Moreover, it discusses the technological hurdles in detecting and remediating PFAS contamination and outlines future research directions aimed at improving analytical methodologies, refining toxicokinetic models, and developing innovative, cost-effective remediation strategies. Additionally, this review underscores the urgent need for coordinated scientific, regulatory, and industrial efforts to mitigate the multifaceted threats posed by PFAS to public health and the environment.

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Introduction

The contamination of our environment by per- and polyfluoroalkyl substances (PFASs) has emerged as one of the most pressing environmental challenges of our time. PFASs represent a vast class of synthetic chemicals that have been extensively employed in various industrial and consumer applications ranging from nonstick cookware and water-repellent fabrics to firefighting foams and stain-resistant products, this widespread use is due to their unique water- and grease-resistant properties [1]. Often termed "forever chemicals" [2], PFASs are characterized by their remarkable chemical stability, allowing them to endure in the environment for decades, if not longer, hence earning the designation "forever chemicals" [3]. As reported by the Centers for Disease Control and Prevention, PFAS can be detected in virtually every environmental compartment, from surface and groundwater to soil and atmospheric deposits, and has even been identified in the blood serum of up to 98% of the U.S. population [4,5]. The significance of PFAS contamination is further highlighted by the fact that over 2,000 sites in the United States alone have been documented as affected by these substances, according to the U.S. Environmental Protection Agency (EPA) [6]. Recent monitoring data indicate that PFAS concentrations in drinking water supplies in several states exceed the newly updated advisory limits, such as the EPA's health advisory levels of 0.004 parts per trillion for perfluorooctanoic acid (PFOA) and 0.02 parts per trillion for perfluorooctanesulfonic acid (PFOS), thereby emphasizing the critical need for ongoing surveillance and regulatory review [7]. These statistics not only highlight the pervasive nature of PFAS but also

Contact Akash Phillip akash.phillip15@gmail.com Department of Biotechnology, IIMT University, Meerut, India.

raise serious concerns regarding long-term human exposure and potential health impacts, such as liver damage, immune system effects, or developmental issues in children [8]. Beyond human health, PFAS contamination poses significant ecological risks as these substances have been found to accumulate in wildlife, leading to disruptions in food webs and ecosystem dynamics [9].

This review paper aims to synthesize current research on PFAS contamination by examining their sources, environmental behavior, and multifaceted impacts on human health and ecological systems. In addition, the review will evaluate current regulatory frameworks and remediation strategies implemented to mitigate PFAS risks. By integrating findings from toxicological studies, environmental monitoring, and policy analysis, the paper seeks to provide a comprehensive perspective on the challenges posed by PFAS and the urgent measures required to address them. The scope of this review encompasses a wide range of impacts associated with PFAS contamination. It will detail the health effects linked to chronic exposure, including endocrine disruption, immunotoxicity, and an increased risk of certain cancers. Moreover, this review will explore ecological consequences, such as bioaccumulation in wildlife and subsequent disruptions in ecosystem services. Regulatory and economic dimensions will also be addressed, focusing on the challenges of establishing enforceable standards and the substantial costs related to remediation efforts. Through the incorporation of recent data, this paper aims to present a holistic understanding of the persistent threat posed by PFAS in our environment.

Historical Background and Chemical Characteristics of PFAS

Historical development of PFAS

The story of PFAS begins in the early 20th century, with a landmark discovery in 1938 when Roy Plunkett, working at DuPont, accidentally created polytetrafluoroethylene (PTFE), the basis for nonstick coatings [10]. This breakthrough paved the way for the development of PFAS-based products, with early industrial applications focusing on PTFE for nonstick cookware and later expanding into protective coatings [11]. During the 1950s and 1960s, companies such as 3M and DuPont harnessed processes such as electrochemical fluorination (or electrofluorination is a method that uses electricity to incorporate fluorine atoms into organic molecules) to mass-produce PFAS compounds, notably perfluorooctanoic acid [12] (PFOA/$C_8HF_{15}O_2$) as illustrated in Figure 1 and perfluorooctanesulfonic acid [12] (PFOS/$C_8HF_{17}O_3S$/$C_8HF_{17}O_3S$) as illustrated in Figure 2. These compounds were soon integrated into a wide array of products. PFOS became a key ingredient in Scotchgard stain repellents, while PFAS-based aqueous film-forming foams (AFFF) revolutionized firefighting [13], especially for military [13] and industrial applications [14]. Despite their commercial success, early studies and emerging scientific evidence from the 1940s onward began to reveal a disconcerting fact [15]. PFAS does not break down naturally [16]. As early as the 1970s, environmental monitoring detected these "forever chemicals" in water, soil, and even human blood, up to 98% of Americans have detectable levels, and over 2,300 contaminated sites have been documented in the United States alone [15]. This persistent presence, combined with growing evidence of adverse health effects [17], prompted major manufacturers to begin phasing out long-chain PFAS in the early 2000s, while their use in consumer products continues through emerging alternatives [18,19].

Chemical properties of PFAS

The unique chemical behavior of PFAS arises from their distinctive molecular architecture. At their

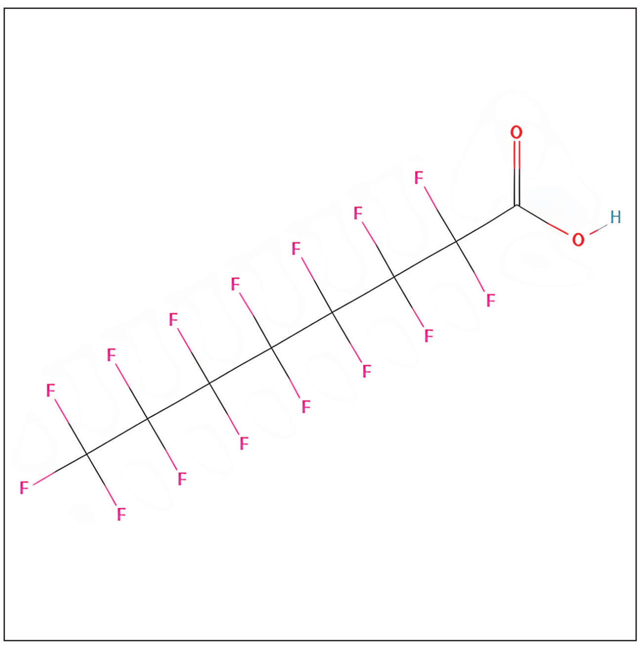

Figure 1. 2D chemical structure of PFOA, a legacy PFAS compound with a perfluorinated carbon chain and a carboxylic acid group [20].

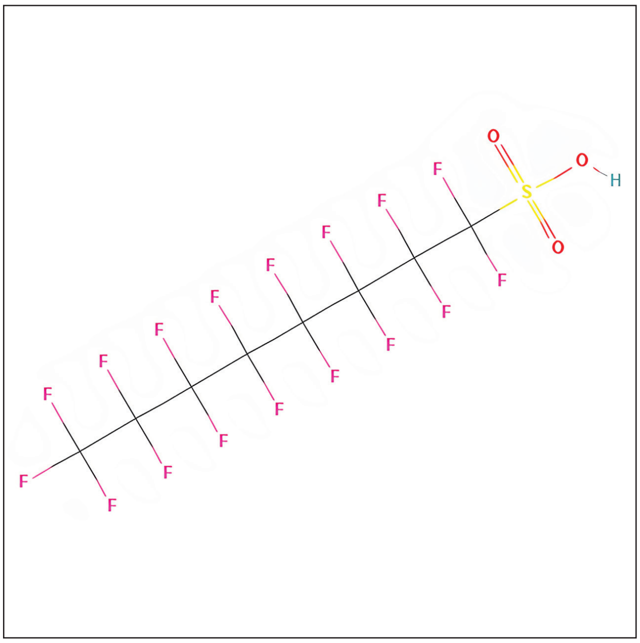

Figure 2. 2D chemical structure of PFOS, featuring a perfluorinated tail and a sulfonic acid functional group [21].

core, PFAS molecules consist of a fully fluorinated carbon chain bonded to a polar functional group, commonly carboxylate or sulfonate [21]. The carbon–fluorine (C–F) bond is among the strongest in organic chemistry, which makes these compounds exceptionally resistant to thermal, chemical, and biological degradation [22]. This remarkable stability is the foundation for their persistence in the environment and explains why they are dubbed “forever chemicals” [3]. Moreover, the molecular design imparts amphiphilic properties, and the fluorinated tail is both hydrophobic and lipophobic, while the attached functional group is hydrophilic [24]. Figure 3 depicts the chemical properties of PFAS that contribute to their persistence in the environment. This duality not only allows PFAS to function effectively as surfactants, reducing surface tension in applications ranging from firefighting foams to stain-resistant coatings, but also facilitates their widespread dispersion and accumulation in living organisms [25]. Their affinity for proteins leads to bioaccumulation, particularly in the liver and blood, and subsequent biomagnification through food chains [26].

The PFAS family is incredibly diverse, with thousands of compounds identified, varying in chain length, branching, and functional groups [27]. Traditionally, long-chain PFASs such as PFOS and PFOA have been the most prevalent and problematic due to their high bioaccumulation potential

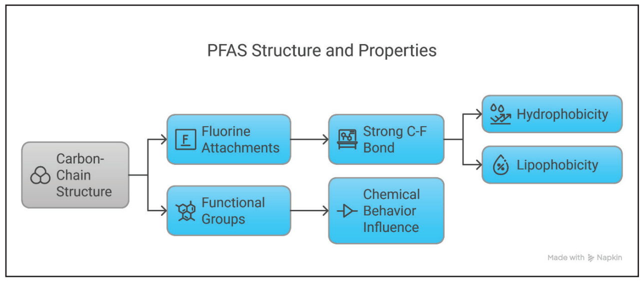

Figure 3. Chemical properties of PFAS that contributes to their persistence in the environment.

[28]. In response to growing regulatory and public health concerns, the industry has begun shifting toward short-chain PFAS (e.g., PFBS) [29]. Although these substitutes are designed to be less bioaccumulative, emerging research indicates that many may still persist and pose similar environmental challenges, underlining the need for continuous assessment and stricter controls.

Sources of PFAS and Pathways of Contamination

PFAS compounds have permeated the environment through a variety of sources and transport mechanisms. Their unique chemical stability not only makes them indispensable in many industrial and consumer applications but also contributes to their persistent, widespread distribution [30].

Industrial and commercial sources

PFAS chemicals have been manufactured and used extensively in industrial processes for over 70 years. Their exceptional resistance to heat, water, and oil makes them ideal for applications such as follows.

Manufacturing processes

PFASs are integral to the production of fluoropolymers, including PTFE (used for nonstick coatings) and other specialized materials [31]. Industrial synthesis methods, such as electrochemical fluorination, have historically generated mixtures containing both target PFAS compounds (e.g., PFOA and PFOS) and various by-products [32].

Consumer products

Beyond the manufacturing sector, PFASs are incorporated into a wide range of consumer goods. Nonstick cookware, waterproof textiles, stain-resistant carpets, and food packaging are all treated with PFAS to impart desirable performance characteristics [33]. The prevalence of these products in everyday life means that PFAS can leach out over time, contributing to ongoing environmental exposure.

Firefighting foams

Aqueous film-forming foams (AFFFs) represent a significant, albeit often overlooked, source of PFAS contamination. These foams are designed to quickly suppress high-intensity fuel fires and are widely used in the following.

Military and airport settings

Military bases, airports, and industrial sites employ AFFF due to their superior fire-extinguishing properties [34]. PFAS compounds, such as PFOS and PFOA, are key ingredients in these foams. When discharged during training exercises or actual fire events, these foams can contaminate nearby soil, surface water, and groundwater [35].

Accidental releases

Beyond intentional applications, accidental spills or improper disposal of firefighting foam residues further contribute to environmental PFAS loads. Historical use of AFFF at fire training sites has left a legacy of PFAS hotspots that continue to challenge remediation efforts [36].

Waste management and discharge

The lifecycle of PFAS-containing products often culminates in waste streams that serve as secondary contamination sources,

Landfills

Discarded consumer products treated with PFAS, such as nonstick cookware, textiles, and paper products, eventually end up in landfills. Here, PFAS can leach into surrounding soils and groundwater, especially since these chemicals resist degradation under typical landfill conditions [37].

Wastewater treatment plants

Many PFASs enter municipal wastewater through domestic and industrial effluents. Conventional wastewater treatment processes are generally ineffective at removing PFAS, meaning that these substances are often discharged into water bodies along with treated wastewater [32]. Moreover, PFAS can accumulate in the sludge generated by these plants, which may later be applied as fertilizer, thereby reintroducing PFAS into the environment [32].

Environmental transport

Once released, PFASs are transported through multiple environmental media, enabling their global distribution [38],

Water

PFASs are highly mobile in water. They can be carried by surface runoff, infiltrate aquifers, and travel significant distances through river systems. Their solubility ensures that once they enter water bodies, they are difficult to contain or remove [39].

Soil

PFASs can bind to soil particles, particularly in areas near landfills, industrial sites, or where wastewater sludge has been applied. Over time, they can gradually migrate from soils into groundwater or be taken up by plants, entering the food chain [40].

Air

Volatilization and the formation of aerosols facilitate the atmospheric transport of PFAS [41]. Wind-driven dust and sea spray can carry these compounds over long distances, depositing them in remote regions far from their original sources [42]. This long-range transport is one of the reasons that PFASs have been detected even in pristine environments like the Arctic [43].

Food chain

Through bioaccumulation and biomagnification, PFAS can concentrate in organisms over time. Low-level exposure through water and soil can lead to elevated levels in wildlife, which, in turn, poses risks to human health via dietary exposure [44]. Together, these sources and pathways underscore the multifaceted challenge of managing PFAS contamination. Table 1 provides a concise summary of the key sources of PFAS contamination and the pathways through which these persistent chemicals disperse in the environment.

Impact of PFAS on Human Health

PFASs can enter the human body through multiple routes, such as through contaminated water supplies, which is a major pathway, especially in communities near industrial sites or military bases where PFASs have been used extensively [45]. For instance, water systems in some U.S. regions have recorded PFAS concentrations exceeding federal

Table 1. Key sources of PFAS contamination and the pathways through which these persistent chemicals disperse in the environment.

Category	Subcategory	Description	Examples	References
Industrial and commercial sources	Manufacturing processes	PFASs are synthesized for the production of fluoropolymers via processes such as electrochemical fluorination. Their unique stability makes them ideal for high-performance applications.	Production of PTFE (used in nonstick coatings) and other specialized materials; generation of mixtures containing target PFAS like PFOA and PFOS along with by-products.	[31,32]
	Consumer products	PFASs are incorporated into many consumer goods to provide water, oil, and stain resistance.	Nonstick cookware, waterproof textiles, stain-resistant carpets, and food packaging; leaching from these products contributes to environmental exposure.	[33]
Firefighting foams	Military and airport settings	Aqueous film-forming foams (AFFF) containing PFAS are used to rapidly suppress high-intensity fuel fires in critical settings.	Widely used on military bases, airports, and industrial sites; PFOS and PFOA are key ingredients; foam discharge during fire events or training exercises contaminates nearby water and soil.	[34,35]
	Accidental releases	Unintended spills or improper disposal of PFAS-containing foams add to the environmental load.	Historical use at fire training sites; accidental spills that create PFAS hotspots challenging remediation efforts.	[36]
Waste management and discharge	Landfills	Discarded PFAS-treated consumer products eventually accumulate in landfills where PFAS can leach into adjacent soil and groundwater.	Nonstick cookware, textiles, and paper products; persistence in landfills due to resistance to degradation under typical conditions.	[37]
	Wastewater treatment plants	PFASs enter municipal wastewater through domestic and industrial effluents. Standard treatment processes are generally ineffective at removing PFAS, resulting in their discharge into water bodies.	PFASs appear in treated wastewater and accumulate in sludge, which may later be used as fertilizer—reintroducing PFAS into the environment.	[32]
Environmental transport	Water	PFASs are highly soluble and mobile in water, facilitating their transport via runoff, infiltration into aquifers, and movement through river systems.	Difficult to contain once in water; long-range transport leads to contamination of surface and groundwater over large areas.	[39]
	Soil	PFASs can adsorb to soil particles, particularly near contamination sources, and gradually migrate into groundwater or be taken up by plants.	Leaching from landfills and industrial sites; accumulation in agricultural soils may lead to entry into the food chain.	[40]
	Air	Volatilization and aerosol formation allow PFAS to be transported through the atmosphere over long distances, depositing in remote regions.	Wind-driven dust and sea spray can carry PFAS; detected even in pristine areas like the Arctic, illustrating their global reach.	[41–43]
	Food Chain	Through bioaccumulation and biomagnification, PFASs concentrate on living organisms over time, increasing exposure levels in species higher up the food chain, including humans.	Wildlife and fish can accumulate PFAS to levels thousands of times higher than in water; dietary exposure through consumption of contaminated food (e.g., fish and crops grown on contaminated soil) poses risks.	[44]

advisory levels [46]. PFASs are known to bioaccumulate in aquatic organisms and wildlife [47]. Consumption of contaminated fish, meat, or crops grown in PFAS-tainted soils can lead to significant dietary exposure [48]. Workers in industries that manufacture or utilize PFAS (e.g., nonstick cookware production and firefighting foam application) are at higher risk due to direct inhalation or dermal contact [49]. Everyday items treated with PFAS, including textiles, paper products, and personal care items, can also be sources of low-level, chronic exposure over time [49]. Various laboratory studies have consistently shown that PFAS exposure can induce a range of adverse biological effects in humans [1], as illustrated in Figure 4.

In controlled studies, exposure to compounds such as PFOA and PFOS has been linked to liver toxicity, as these chemicals can accumulate in the liver and disrupt normal function [49]. This can lead to conditions such as fatty liver disease and elevated liver enzymes [50], for example, rodent models [51] have demonstrated that high doses of these chemicals lead to liver enlargement, altered lipid metabolism, and changes in thyroid hormone levels and lower birth weight [52]. Immune system impairment, PFAS has been shown to weaken the immune system, reducing the body's ability to fight infections and respond to vaccines [53]. This is particularly concerning for vulnerable populations, such as children and the elderly [54]. PFAS can interfere with the endocrine system, which regulates hormones in the body [55]. This disruption can lead to various health issues, including reproductive problems [56], developmental delays in children [57–60], and altered metabolism [61]. Epidemiological research in humans further supports these findings [62]. Data from the Centers for Disease Control and Prevention (CDC) indicate that nearly 98% of the U.S. population have detectable levels of PFAS in their blood [63]. Longitudinal studies have found associations between elevated PFAS serum concentrations and increased risks for several cancers [64], including kidney [65] and testicular cancer [66], as well as thyroid disease [67] and high cholesterol [68].

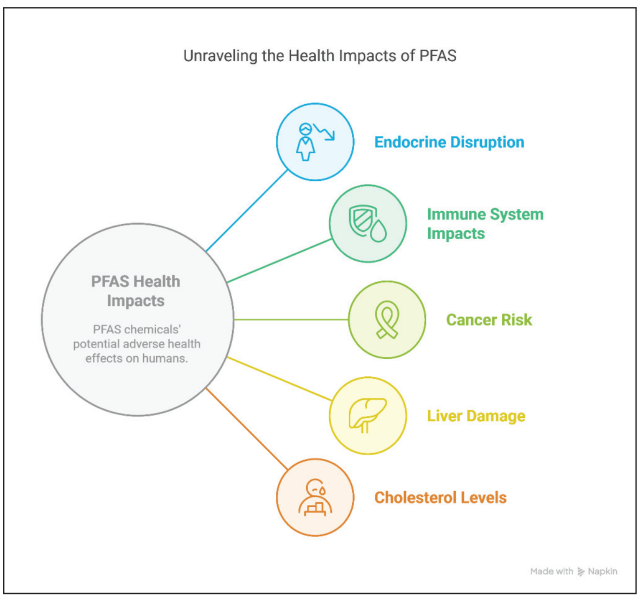

Figure 4. Major human health effects associated with PFAS exposure, including liver, immune, endocrine, and cancer risks.

However, assessing the real-time human health risks posed by PFAS is complex and involves several challenges. With thousands of PFAS variants in circulation, each compound has its toxicological profile. This diversity complicates efforts to establish universal risk thresholds. Many PFASs, such as PFOA, have long half-lives (approximately 3–5 years in humans), meaning that they persist in the body and can accumulate over time even with low-level exposure [69]. Humans are typically exposed to mixtures of different PFAS. Current risk assessment methodologies often focus on single compounds, and the cumulative or interactive effects of multiple PFAS remain poorly understood. While epidemiological studies have provided valuable associations between PFAS exposure and health outcomes, confounding factors and the long latency periods of some diseases (like cancer) add uncertainty to risk estimates. Moreover, extrapolating animal study results to human populations requires the use of uncertainty factors, which may vary widely between studies. The U.S. EPA has set health advisories for PFOA as low as 0.004 parts per trillion and PFOS at 0.02 parts per trillion in drinking water [70]. These extremely low levels highlight the sensitivity of current risk assessments but also pose practical challenges for enforcement and remediation.

Impact of PFAS on Ecological and Environment

PFAS contamination poses significant risks to wildlife and ecosystems, impacting both aquatic and terrestrial species [1], as depicted in Figure 5.

Wildlife exposure

PFASs are frequently detected in fish, amphibians, and invertebrates [71]. For example, studies have shown that in some U.S. water bodies, freshwater fish can have PFOS concentrations exceeding environmental quality thresholds. Profiling analysis has reported that around 12% of fish samples had PFOS levels above 9 μg/kg, with certain species like flounder and roach reaching levels as high as 34–41 μg/kg [72,73]. Such high concentrations not only endanger the fish themselves but also pose risks for predators that feed on them, including birds and mammals [74]. PFASs have also been documented in a wide range of terrestrial animals [75], from birds [76] to mammals. Top predators such as otters and birds of prey often show some of the

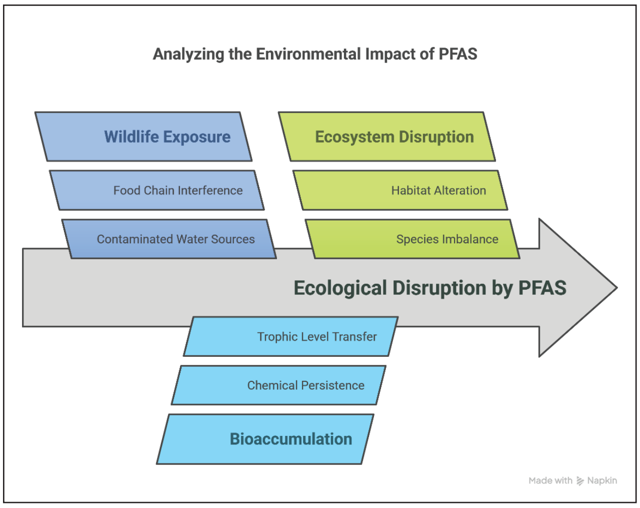

Figure 5. Ecological impacts of PFAS, such as bioaccumulation, trophic transfer, and disruption of ecosystem services.

highest burdens [77]. Recent data have revealed that otters had PFAS concentrations up to 9,962 μg/kg in their tissues [78]. Similarly, reports on harbor porpoises [79] and gray seals [80] indicate levels of 2,420 μg/kg and up to 357 μg/kg, respectively. These elevated concentrations are a clear sign of the persistent nature of these chemicals in various ecosystems.

Risk of bioaccumulation and biomagnification

PFASs are characterized by strong carbon–fluorine bonds that resist degradation. Their amphiphilic nature allows them to bind to proteins, which means that they preferentially accumulate in organs such as the liver and blood [81]. Studies using trophic magnification factors (TMFs) have demonstrated that PFAS concentrations can increase significantly along food chains [82]. In some aquatic–terrestrial food webs, biomagnification factors for PFOS have ranged from 4.6 to nearly 20, while PFDA has shown biomagnification factors as high as 27 [83,84]. These values indicate that predators at the top of the food chain may accumulate PFAS levels thousands of times higher than those in the surrounding water. The bioaccumulation is not uniform across all PFAS compounds. Long-chain PFASs such as PFOS and PFDA are more bioaccumulative, whereas some short-chain alternatives may degrade under certain conditions [85]. As a result, apex predators, including certain bird species and mammals, exhibit particularly high concentrations. This process can compromise the health of these species, as the persistent buildup of PFAS interferes with normal physiological functions.

Disruption of ecosystem

The persistence and bioaccumulation of PFAS can lead to disruptions in reproductive success and immune function across various species [86]. Elevated PFAS levels in bird eggs have been linked to decreased hatching success and increased nest failure [87]. Similar reproductive impairments have been observed in amphibians and fish, potentially leading to long-term population declines [88]. PFAS contamination in soil and water affects more than just individual species, it disrupts entire ecosystems [48]. In aquatic environments, high PFAS levels can affect the growth and reproduction of invertebrates, which serve as a crucial food source for higher trophic levels [89]. This disruption cascades through the food web, ultimately impacting ecosystem services such as water purification, fisheries, and even pollination if terrestrial invertebrates are affected [90]. The contamination of water bodies and soils with PFAS has led to fish consumption advisories in several regions [91], which not only impacts human health but also the livelihoods of communities reliant on fishing [92].

Regulatory Challenges in the Mitigation of PFAS

The fight against PFAS contamination is complicated by persistent scientific, technological, and policy challenges.

Limitations in the toxicological data

Although extensive research on legacy PFAS such as PFOS and PFOA has established links to cancer, endocrine disruption, immunotoxicity, and other chronic conditions, data on many emerging or replacement PFAS remain scarce [93,94]. Long-term exposure effects, especially at low doses over decades, are not well understood. Uncertainties persist in the toxicokinetics of PFAS, such as differences in absorption, distribution, metabolism, and excretion between species [4,62]. For example, while nearly 98% of Americans have detectable PFAS in their blood, the cumulative impacts of chronic low-level exposure on vulnerable populations are still being defined [3,62]. In real-world settings, humans and wildlife are exposed to complex mixtures of PFAS [63]. The additive or potentially synergistic effects of these mixtures complicate risk assessments, as most studies focus on individual compounds rather than combined exposures.

Technological challenges in PFAS detection

The vast chemical diversity of PFAS (over 14,000 compounds) means that conventional targeted analytical methods (e.g., LC-MS/MS) often capture only a fraction (<50%) of the total PFAS burden [21, 25]. Many precursor compounds remain undetected due to the limited availability of analytical standards and nonstandardized methodologies. PFAS' resistance to natural degradation, due to their strong carbon–fluorine bonds, makes effective remediation challenging. Current treatment technologies such as thermal destruction, advanced oxidation, and adsorption on activated carbon are energy intensive, expensive, and sometimes produce harmful byproducts [23]. For instance, remediation costs at contaminated sites in England have been projected to reach up to 121 billion pounds in worst case scenarios [95,96].

Challenges in present policies and legislation addressing PFAS

Most regulatory frameworks focus on a narrow subset of PFAS (e.g., PFOS and PFOA), leaving thousands of related compounds unregulated. This creates gaps in protecting public health and ecosystems, particularly as industries shift toward alternative PFAS that may be just as harmful [8]. Scientific findings regarding the toxicity and environmental persistence of PFAS are advancing rapidly, yet policies often lag [97]. Outdated standards may not reflect the latest evidence on low-dose, long-term exposures or the risks associated with PFAS mixtures. Moreover, international regulatory approaches vary, with the U.S., EU, Australia, and others taking different stances, complicating global efforts [98]. High-profile litigation cases have resulted in multibillion-dollar settlements for PFAS contamination [99]. The enormous cleanup costs, coupled with the financial burden on industries and water providers (e.g., capital and operating costs that could significantly raise water bills), underscore the urgent need for regulatory reforms that incentivize the reduction of PFAS use at the source [92]. Therefore, on January 13, 2023, five member states presented a restriction proposal to the European Chemicals Agency (ECHA) regarding PFAS under the REACH Regulation, aiming to prohibit their manufacture and use in nonessential applications [100], along with The United Nations Human Rights Council that has condemned DuPont and Chemours for extensive PFAS contamination in North Carolina, particularly affecting communities along the Cape Fear River [101]. UN experts allege that these companies knowingly discharged toxic PFAS chemicals from the Fayetteville Works facility for decades, contaminating air, soil, water, and food supplies, and infringing upon residents' rights to health, clean water, and a safe environment [102].

Future Research Directions

In order to bridge the existing gaps and tackle the challenges associated with PFAS, it is imperative to propose subsequent research initiatives that emphasize interdisciplinary studies, thereby fostering collaborations among environmental chemists, toxicologists, epidemiologists, and engineers, which would facilitate the integration of diverse areas of expertise to comprehensively address the multifaceted nature of PFAS exposure and its corresponding effects [103]. Furthermore, the development and standardization of advanced nontargeted screening methodologies, such as high-resolution mass spectrometry and APP-ID coupled with machine learning-enhanced surface-enhanced Raman scattering (SERS) achieved detection limits as low as 1 ppt for PFOA and 4.28 ppt for PFOS, with classification accuracy reaching up to 95% utilizing support vector machines [104,105] along with total fluorine analysis, are essential to capture the complete spectrum of PFAS, which includes both emerging compounds and their precursors [25,106]. Additionally, the execution of long-term studies aimed at monitoring PFAS levels in both human populations and wildlife is crucial for enhancing our understanding of the effects of chronic exposure, interspecies variations in toxicokinetics, and the cumulative consequences of low-dose exposures [107]. Furthermore, there is a pressing need to invest in research that focuses on cost-effective, scalable, and energy-efficient remediation strategies capable of achieving the destruction of PFAS without generating harmful byproducts [108]. Moreover, it is vital to place additional emphasis on policy-oriented research that quantifies the socioeconomic ramifications of PFAS contamination to effectively inform and propel necessary policy changes [90,109]. This encompasses conducting comprehensive risk assessments, ensuring transparent reporting by industry stakeholders, and examining the correlations between regulatory actions and subsequent improvements in environmental and public health outcomes.

Conclusion

PFAS contamination presents a complex and persistent environmental and public health concern, and several critical challenges remain in effectively managing these substances. One of the most pressing issues is the lack of comprehensive toxicological and epidemiological data on the vast number of newer PFAS compounds. While legacy chemicals such as PFOA and PFOS are well-studied, the health effects of many emerging alternatives, especially under chronic, low-dose, and mixed exposures, are still not well understood. Another major challenge lies in the limitations of current detection and treatment technologies, which often fail to capture or fully remove PFAS at the low concentrations found in the environment. There is a clear need for more advanced, nontargeted detection methods and more efficient, scalable remediation strategies. Additionally, regulatory systems have not kept pace with scientific advancements, resulting in thousands of PFAS chemicals remaining unregulated. Bridging this gap between science and policy through interdisciplinary collaboration and robust risk assessments is crucial. Addressing these knowledge and regulatory gaps is key to understanding the full scope of PFAS contamination, reducing its impacts on health and ecosystems, and guiding effective future responses.

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Conflict of interest

There is no conflict of interest to be stated.

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