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Review Article

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A Review on Per- And Polyfluoroalkyl Substances (PFAS) in Water and Consumer Products

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a wide range of synthetic fluorinated chemicals, most commonly known for their persistence and ubiquitous presence in the environment, and the potential for adverse health effects. We present a review of the studies (2015-2025) on the chemistry, environmental occurrence, analyses, remediation and regulation of PFAS, using a synthesis approach based on PRISMA. After an extensive search of the literature in the main scientific databases and agencies, over 480 reports were found relevant to this review. PFAS are more than 15,000 chemicals with different physical-chemical properties that influence their environmental fate, transport and accumulation. Using sophisticated analytical techniques, micro contamination can be detected at extremely low levels (ng/L) in water, food and humans. Traditional removal methods, such as granular activated carbon and ion exchange, are highly efficient for long-chain PFAS, but short-chain PFAS are very mobile and difficult to remove. New techniques for destruction, such as plasma destruction and supercritical water oxidation, guarantee higher than 99% degradation under laboratory conditions. Regulation is getting tougher with improved drinking water quality standards and the introduction of a management class system. However, monitoring ability and regulatory actions are not standardised. This review highlights the knowledge gaps and the need for the scalable remediation technologies, global regulatory harmonisation to reduce the long-term risks of PFAS, and the application of the essential use framework for effective mitigation of risks of PFAS.

1. INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are a heterogeneous category of synthetic fluorinated materials and have an astonishing chemical stability, a high level of environmental stability, and degradation resistance. The carbon-fluorine bond is so strong that PFAS have become known as forever chemicals, resistant to disintegration under thermal, chemical, and biological reactions in nature (Brunn et al., 2023; Cousins et al., 2020). Their vast industrial and commercial usage, such as firefighting foams, non-

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stick surfaces, clothing and food wrapping, has spread widely around the globe when it comes to all environmental divisions. All of the latest research has shown that PFAS are widespread in surface and groundwater, soil, and the air, and their presence has often been detected in ultra-trace levels (ng/L) of drinking water and environmental samples (Teymoorian et al., 2023; Shen et al., 2024). High mobility and bioaccumulative potential cause long-distance transport and biomagnification by food chains, and this leads to human exposure to contamination through ingestion, inhalation, and dermal exposure (Domingo and Nadal, 2019; Guelfo et al., 2021).

PFAS have been increasingly associated with detrimental health effects, including endocrine disruption, immunotoxicity, and carcinogenicity, which poses a major problem to the health of the population (Donley et al., 2024). To a large extent, the environmental monitoring, risk assessment, and remediation of PFAS are challenging due to the structural diversity of over 15,000 compounds (Cousins et al., 2020). The standard analytical methods have been developing in order to observe smaller concentrations of PFAS; nevertheless, there are also weaknesses in the identification of new and unknown types of PFAS (Rehman et al., 2023; Baqar et al., 2025). On a similar note, the conventional water treatment methods like adsorption and filtration can only work with long-chain PFAS, against short-chain analogues that are more mobile and difficult to eliminate (Bharti, 2025). Regardless of the increasing regulatory interest, the existing policies are still rather unshielded and usually target each specific compound instead of the whole PFAS group, which reduces their efficiency when it comes to the cumulative environmental risks (Cousins et al., 2020; Yu et al., 2025). Moreover, the unequal presence of monitoring facilities and compliance with regulations across the geographical areas contributes to the worldwide spread of the problem of PFAS contamination.

Despite the fact that various research studies have been conducted on the particular dimensions of PFAS behaviour, there is limited synthesis of the progress in the field of chemistry, environmental presence, analytical identification, remediation methods, and legislative systems. This review fills this gap by systematically and up-to-date reviewing the state of PFAS research published in 2015-2025 with a view to determining key gaps in knowledge, technological constraints, and future research areas of interest. Integrating interdisciplinary knowledge, the work will be designed to assist in the development of efficient mitigation options and policy-making in terms of sustainable management of PFAS.

2. METHODOLOGY

This review was conducted in a systematic and orderly fashion following the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to provide transparency, reproducibility and rigour (Page et al., 2021). A literature review was carried out in search of reputable scientific databases, including Scopus, Web of Science, PubMed and Google Scholar, for the period of January 2015 to October 2025. Other data were obtained from the reports published by regulatory agencies such as the United States Environmental Protection Agency (USEPA), European Chemicals Agency (ECHA) and World Health Organisation (WHO). We used a combination of search terms such as PFAS, per- and polyfluoroalkyl substances, environmental occurrence, analytical detection, remediation and regulation. The preliminary search produced a total of 1,245 records. After removing the duplicate records (n = 600), 645 records were screened on the basis of titles and abstracts. Articles were removed if they were not related to PFAS, not scientifically complete or written in a language other than English. As a result, 485 articles were selected for full-text assessment. Articles were also excluded if they did not meet the set inclusion criteria, such as suitability in terms of relevance to PFAS chemistry, distribution, analytical methods, remediation or regulation. The resulting set of peer-reviewed articles was 485 articles, which were systematically reviewed and put into thematic groups, such as PFAS chemistry and classification, environmental occurrence and exposure pathways, analytical methods of detection, remediation technologies, and regulatory frameworks. Key findings, methodological approaches, and limitations were targeted in data extraction to be able to synthesise current knowledge in a complete and critical manner.

3. CHEMISTRY AND CLASSIFICATION OF PFAS

PFAS (Per- and polyfluoroalkyl substances) refer to a family of heterogeneous synthetic compounds of organofluorine that contain at least one completely or partially fluorinated chain of carbon. The existence of a strong carbon-fluorine (C-F) bond is one of the strongest in the context of organic chemistry and develops resistance to thermal, chemical, and biological degradation, which explains the high level of stability of PFAS (Buck et al., 2011; Cousins et al., 2020). PFAS may be broadly classified into two major groups, including perfluoroalkyl substances, in which no hydrogen atoms are present in the alkyl chain, but fluorine atoms have substituted them, and polyfluoroalkyl substances, in which carbon chains are partially replaced with fluorine atoms (Buck et al., 2011). It is a significant difference, and polyfluoroalkyl compounds can be used to create more resilient types of perfluoroalkyl acids (PFAAs), including perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) (Guelfo et al., 2021). PFAS could be categorised into non-polymeric and polymeric in accordance with their chemical structure and functional groups. Non-polymeric (PFAS) (such as perfluoroalkyl acids, PFAAs) (carboxylates and sulfonates) are highly abundant in the environmental matrices due to their stability and solubility. The industrial processes often use polymeric PFAS, including fluoropolymers and side-chain fluorinated polymers, which may release smaller PFAS with time (Fiedler et al., 2020; Buck et al., 2021). Chain length is also an important classification parameter, which is often used to distinguish between long-chain PFAS (> C8 in carboxylates and > C6 in sulfonates) and short-chain PFAS. PFAs have a higher propensity to bioaccumulate and prove to be toxic in long-chain forms, whereas short-chain forms are more mobile and persistent in the water, making them difficult to eliminate (Cousins et al., 2020; Guelfo et al., 2021). The recent advances in the classification of PFAS have underscored the need for classification methods because of the extraordinarily large number of compounds (>15,000) and the range of structures. In order to improve risk assessment and risk management, the use of substance-by-substance evaluation has been proposed to be ineffective, and the system of cheminformatics-based classification and class-based frameworks should be employed (Schymanski et al., 2023; Secundo & Metrangolo, 2025). Overall, the heterogeneity of the structure of the PFAS, the routes of their modification, and the various physicochemical characteristics of the molecules have a significant role to play, since they influence the environmental behaviour, detection, and treatability of the compounds. The classification of PFAS is a short definition, which is therefore central to the useful monitoring tools and remediation technologies.

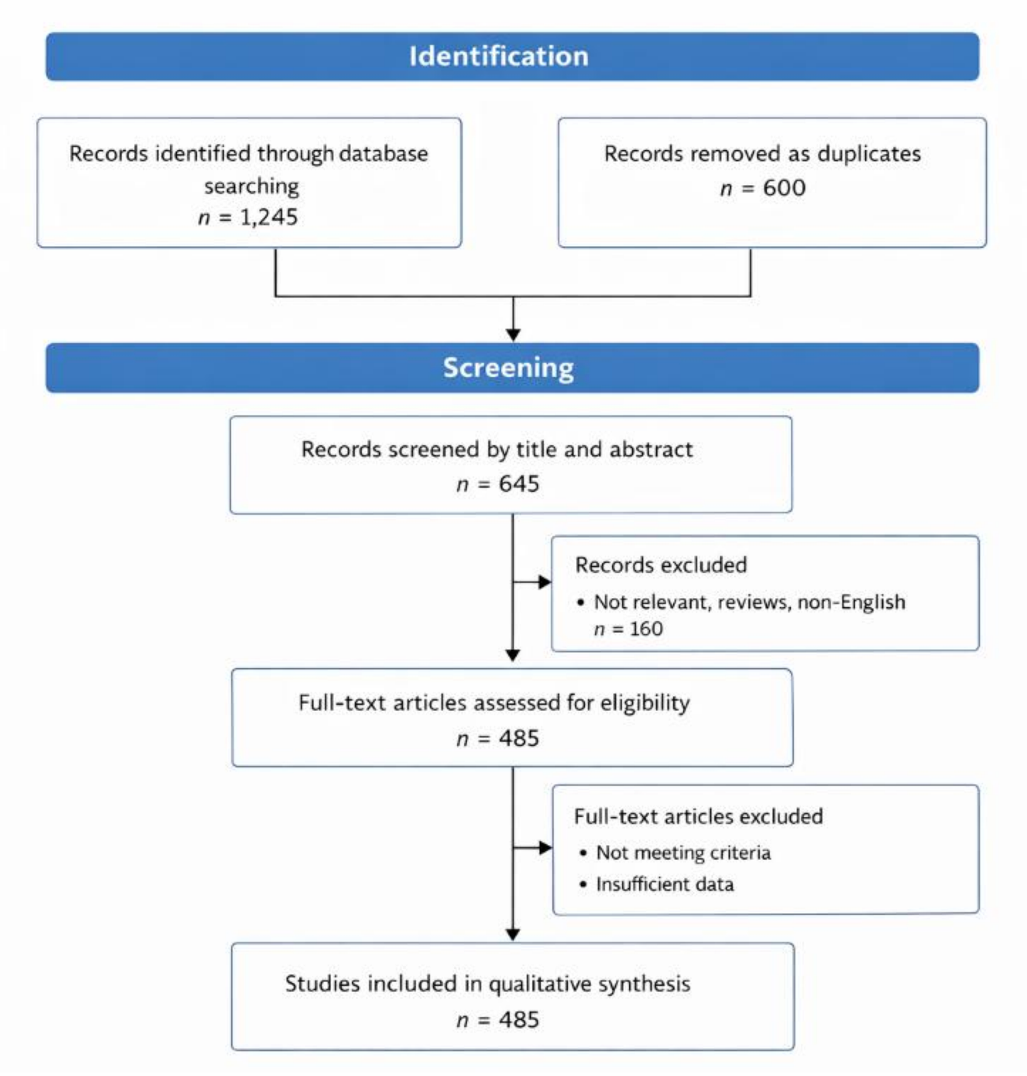

Figure 1. PRISMA 2020 flow diagram illustrating the literature selection process for PFAS studies published between 2015 and 2025

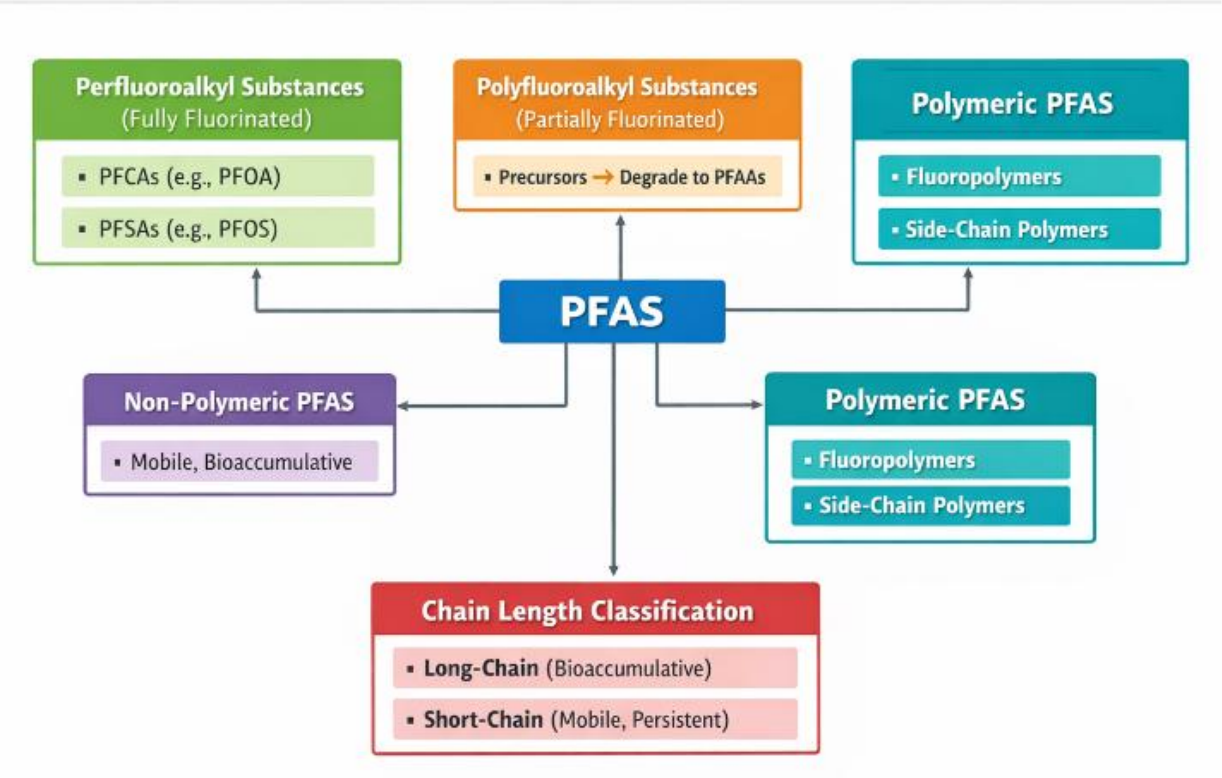

Figure 2. Major classes of PFAS, with example compounds, functional group characteristics, common uses, and notes on persistence/mobility (Buck et al., 2011; Cousins et al., 2020; Guelfo et al., 2021)

4. SOURCES AND ENVIRONMENTAL OCCURRENCE OF PFAS

PFAS are emitted into the environment by the different industrial, commercial, and consumer-related processes that cause them to be widely distributed globally in the different compartments of the environment. Key sources are aqueous film-forming foams (AFFF), the manufacture of fluoropolymers, textile and paper treatment, metal plating, and waste disposal (landfill and wastewater treatment) (Guelfo et al., 2021; Abunada et al., 2020). PFAS are emitted to the environment through point sources and diffuse sources. Industrial plants, firefighting training facilities, and wastewater treatment plants are some of the common places where point sources are usually associated with high concentrations of PFAS being directly discharged to the surrounding soil and water systems. Diffuse sources, on the other hand, include consumer product degradation, urban runoff, and atmospheric deposition, which generate a low-level contamination of areas on a large scale (Brunn et al., 2023; Benaafi and Bafaqeer, 2024). PFAS have been widely reported to be present in the environment of surface water, subsurface water, soil, sediments, air and biota, all over the world. PFAS have been detected in drinking water sources at ng/L to µg/L, and higher concentrations have been reported around contaminated regions like AFFF-impacted areas and industrial areas (Teymoorian et al., 2023; Mussabek et al., 2022). The soil systems can both act as a sink and a secondary source, storing long-term storage and then being released to the groundwater and surface water systems (Brusseau et al., 2020). PFAS chain length, functional groups and solubility determine the transport pathways of the chemical. Long-chain PFAS are more likely to adsorb onto organic matter and sediments, and short-chain PFAS are more mobile and easily distributed by the aquatic systems (Guelfo et al., 2021; Lyu et al., 2022). Atmospheric delivery is an important way, facilitating long-range dispersion and deposition in distant areas, such as polar areas (Baqar et al., 2025). PFAS are mostly ingested in drinking water, by diet, and in indoor settings, where inhalation and dermal contact are also involved. Current literature stressed the necessity to focus on the role of indoor dust and consumer goods as critical routes of exposure (especially in urban environments) (DeLuca et al., 2022; Domingo and Nadal, 2019). On the whole, the widespread presence and complicated transport chains of PFAS evoke the idea of classification into the category of contaminants that are distributed globally. Their resistance, movement, and the constant discharge by the primary and secondary sources pose great problems to the environment monitoring, risk evaluation and remediation processes.

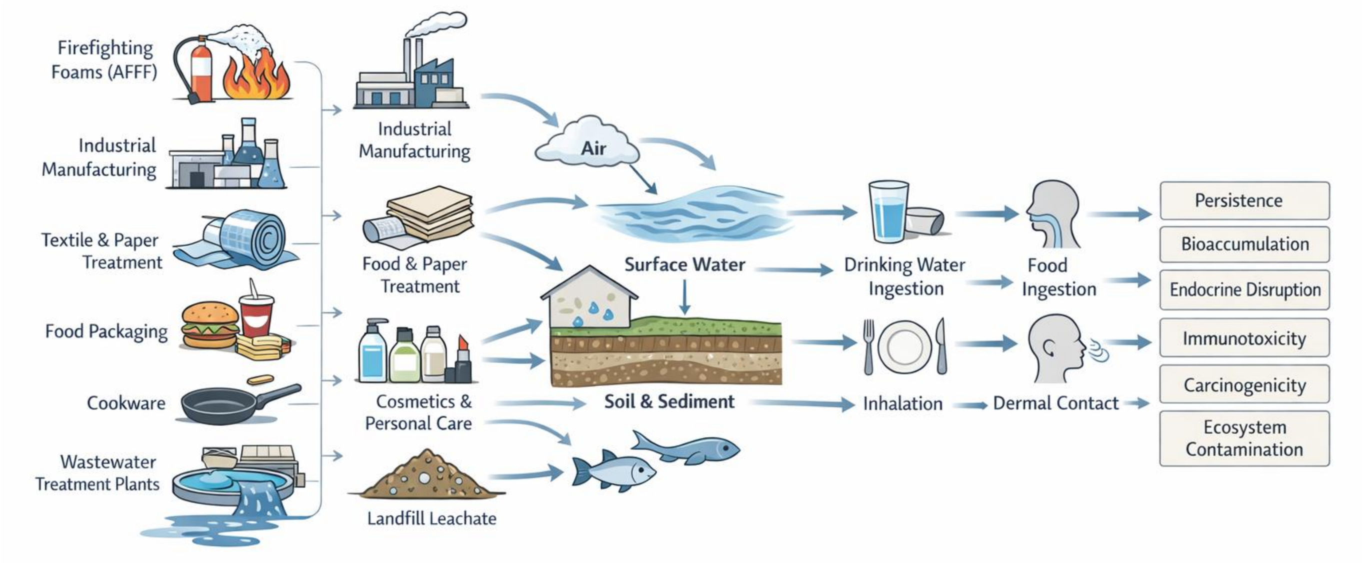

Figure 3. Sources, environmental transport, and human exposure pathways of PFAS

5. ANALYTICAL DETECTION METHODS FOR PFAS

The proper identification and measurement of the per- and polyfluoroalkyl substances (PFAS) in the environmental matrices is essential to comprehending their presence, transport, and risks. PFAS analysis needs sensitive and selective methods of analysis due to their structural diversity, as these toxins occur in the form of ultra-trace concentrations (Rehman et al., 2023; Shen et al., 2024). The targeted PFAS analysis has the highest rate of use based on liquid chromatography coupled with tandem mass spectrometry (LC–MS/MS), which has a high sensitivity, selectivity, and measurement at the levels of ng/L in water and other environmental samples (Teymoorian et al., 2023; Nahar et al., 2023). The method is especially efficient in determining leftover PFAS products, including PFOA and PFOS, but only in predetermined target analytes, and it could fail to identify uncharacterized and emerging PFAS products. In order to overcome these drawbacks, non-target and suspect screening of PFAS has been performed with high-resolution mass spectrometry (HRMS), such as time-of-flight (TOF) and Orbitrap-based instruments, more and more. The methods help to determine the previously unidentified compounds and transformation products and broaden the knowledge of the PFAS contamination profiles (Baqar et al., 2025; Wang et al., 2023). Besides targeted and non-targeted methods, total fluorine-based techniques, including particle-induced gamma-ray emission (PIGE) and combustion ion chromatography (CIC), are complementary methods of evaluation in that they are used to measure the total organofluorine content. The techniques are especially applicable in determining the existence of unidentified PFAS but do not provide specific compound resolution (Androulakakis et al., 2022; Kärrman et al., 2021). New sensing methods have also been developed recently, such as surface-enhanced Raman spectroscopy (SERS) and electrochemical sensors that provide cost-effective and fast detection opportunities. Nevertheless, these techniques have not reached a final stage and still need additional testing in order to be used regularly during environmental monitoring. Although major advances have been made, issues in PFAS analysis, such as interference with the matrix, the absence of standard methods of analysis of emerging compounds, and the unavailability of reference standards of most PFAS species, all persist. It is thus advised that combined analytical methods incorporating targeted and non-targeted analysis, coupled with a total fluorine analysis, be used to provide a complete characterisation of PFAS.

6. REMEDIATION TECHNOLOGIES FOR PFAS

PFAS are highly chemically stable, non-degradable, and exhibit varying physicochemical characteristics, which are the main reasons why their remediation poses a strong challenge. The existing methods of treatment can be generally divided into two types: separation technologies and destruction technologies that have their unique pros and cons (Meegoda et al., 2022). The most common technologies that have been used in the separation of PFAS in contaminated water systems are separation-based technologies. The most widely used of them are granular activated carbon (GAC) and powdered activated carbon (PAC), which have a high adsorption capacity against long-chain PFAS. On the same note, anion exchange resins (AIX) are also more selective and efficient, especially in eliminating negatively charged PFAS species (Bharti, 2025; Chow et al., 2022). Processes based on membranes, such as nanofiltration (NF) and reverse osmosis (RO), offer an efficient removal rate of a wide variety of PFAS compounds; nevertheless, they produce concentrated waste streams that necessitate further treatment (Tow et al., 2021). The effectiveness of separation technologies does not remove PFAS; actually, they convert them into second streams of waste that are of concern about the issue of disposal and the environmental consequences in the long term. By comparison, the purpose of the destruction technologies is to mineralise the PFAS into less toxic substances, thus providing a more sustainable solution. Some of the emerging destruction techniques are advanced oxidation processes (AOPs), plasma-based treatment, electrochemical oxidation, and supercritical water oxidation (SCWO). These technologies have shown great degradation efficiencies with high degradation rates of 90 and above or 99 and above when optimised (Meegoda et al., 2022; Yaghoobian et al., 2025). Among them, there is a special promise to plasma and electrochemical processes, which allow destroying the strong C-F bond. Nevertheless, there are still issues of energy demand, scalability and developing potentially harmful by-products. They have also investigated biological treatment methods, but PFAS are generally not biodegradable, so using the standard bioremediation methods is not very effective. The recent studies are exploring the hybrid systems that combine adsorption and destruction steps to improve the overall efficiency of treatment. In general, although great progress has been achieved in the remediation of PFAS, there is no kind of technology that can be considered universal to address it. The sustainability of the management of PFAS requires a combined style of separation and destruction, enhanced optimisation of the processes and lifecycle analysis.

7. REGULATORY FRAMEWORK AND FUTURE OUTLOOK

The growing awareness of the persistence and toxicity of per- and polyfluoroalkyl substances (PFAS) has prompted a surge in regulatory activities around the world. However, regulatory decisions can vary from one region to another due to differences in approaches to risk assessment, analytical capabilities, and policy priorities (Cousins et al., 2020; Yu et al., 2025). In the US, the Environmental Protection Agency (USEPA) has set increasingly low health advisories for major PFAS in drinking water (such as PFOA and PFOS), and is in the process of finalising maximum contaminant levels (MCLs). The European Union has also taken a precautionary stance by proposing to restrict the whole PFAS class under the REACH regulation, moving towards class-based regulation (Cordner et al., 2019; Cousins et al., 2020). In other areas, such as Canada and Australia, regulatory guidelines and monitoring programs have been introduced but vary in regulatory levels and enforcement. The challenge with regulating PFAS is the sheer number of compounds and the ongoing development of alternatives, making risk assessment on a compound-by-compound basis difficult. As a result, there is a growing trend towards group-based regulation, and the inclusion of the "essential use" principle, which limits the use of PFAS to those deemed essential for human health, safety or critical societal needs (Cousins et al., 2020; Yu et al., 2025). However, there remain considerable challenges in global PFAS management. Developing nations often lack the monitoring systems, regulatory frameworks and technical expertise for effective management of PFAS contamination (Adewuyi & Li, 2024). Lack of standardised analytical techniques and reporting practices also poses challenges for data consistency. Research and policy needs to focus on the establishment of standardised monitoring guidelines, cost-effective and scalable remediation strategies, and holistic risk assessment approaches that address mixture effects and chronic exposure. The use of high-tech analytical methods, data analytics and life cycle assessment will also inform decision making. Finally, global coordinated action and standardised approaches are critical to address the worldwide threat of PFAS.

8. CONCLUSIONS

PFAS are chemicals that pose a major and long-lasting environmental issue because of their chemical stability, prevalence, and their possible negative health impacts. This is a review of current developments in the chemistry, environmental distribution, analytical detection, remediation technologies and regulation systems of PFAS, as well as the multi-layered nature of dealing with such compounds in various environmental systems. Although there has been a significant advancement in the techniques of analysis and solutions, there are still critical challenges. The large range of PFAS compounds, the new ones and the unknown ones, still contributes to the inability to effectively monitor and risk assess. Although the current treatment technologies are efficient in removing long-chain PFAS, short-chain analogues are extremely mobile and difficult to remove, which implies the necessity to develop more efficient and scalable methods. New methods of destruction have potential but still need to be optimised to be put into practice. There is a shift towards class-based regulation and towards the introduction of the essential-use concept, but there are still considerable gaps between the regulatory capacity and regulatory enforcement in the world. The strategies to fill these gaps will require global collaboration, standardised approaches and increased information exchange. Integrated analytical frameworks, remediation technologies which are sustainable, and risk assessment strategies that are holistic and consider the mixture effects and long-term exposures should be the focus of future studies. An international, multidisciplinary solution to the problem of PFAS contamination is required to reduce the impact and protect the environment and human life.

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