Review

# Emergency of per- and polyfluoroalkyl substances in drinking water: Status, regulation, and mitigation strategies in developing countries

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## ARTICLE INFO

## ABSTRACT

The detection of per- and polyfluoroalkyl substances (PFAS) in water presents a significant challenge for developing countries, requiring urgent attention. This review focuses on understanding the emergence of PFAS in drinking water, health concerns, and removal strategies for PFAS in water systems in developing countries. This review indicates the need for more studies to be conducted in many developing nations due to limited information on the environmental status and fate of PFAS. The health consequences of PFAS in water are enormous and cannot be overemphasized. Efforts are ongoing to legislate a national standard for PFAS in drinking water. Currently, there are few known mitigation efforts from African countries, in contrast to several developing nations in Asia. Therefore, there is an urgent need to develop economically viable techniques that could be integrated into large-scale operations to remove PFAS from water systems in the region. However, despite the success achieved with removing long-chain PFAS from water, more studies are required on strategies for eliminating short-chain moieties in water.

## 1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are halogenated organic molecules of industrial applications that cut across food, textile, cosmetics, and household products. Despite the successes recorded with the use of PFAS, direct ingestion into the human system has health challenges, making it unfit for healthy living. Therefore, using some selected PFAS as bulk resources or additives in industrial production is prohibited [1]. Unfortunately, PFAS are currently detected in drinking and drinking water sources, a situation that calls for serious public health concerns and urgent attention.

PFAS are environmentally persistent substances [2] with health hazard concerns, making them environmentally unfriendly. The toxicological profile of most PFAS needs to be better understood, and with the growing concerns, there are reasons to discontinue their production. However, this move is unlikely and impractical because of the essential role PFAS plays in products associated with safety (e.g. fire retardant, building material, etc.) and health (surgical implants, surgical gloves, blood bags, orthopedic components, etc.). Generally, PFAS are a group of compounds containing the moiety $-C_nF_{2n+1}$ and $-C_nF_{2n}-(n \geq 1)$ in their structure [3,4]. Interestingly, other authors have included cyclic, aromatic, and substituted fluorinated compounds [5]. Some identified groups include perfluoroalkyl acids (PFAA), fluorotelomer-based substances, and perfluoroalkane sulfonyl fluoride (PASF)-based substances. These groups may be polymeric or non-polymeric substances. Examples of nonpolymeric substances include nonpolymeric PASF-based substances and non-polymeric fluorotelomer-based substances. This category encompasses various compounds such as perfluoroalkyl carbonyl fluoride (PACF)-based substances, perfluoroalkyl phosphinic acids (PFPIA)-based substances, cyclic PFAS, aromatic substances with fluorinated sidechains, per- and polyfluoroalkyl ethers, and hydrofluoroether. The polymeric substances include perfluoropolyether, fluoropolymers, sidechain fluorinated polymers, etc (Fig. 1).

PFAS are present in the environment and have generated global discussion due to their resistance to hydrolysis, biodegradation, and photooxidation [6,7]. The typical PFAS are perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), perfluorobutane sulfonic acid (PFBS), perfluorosulfonic acids (PFSA), hexafluoropropylene oxide
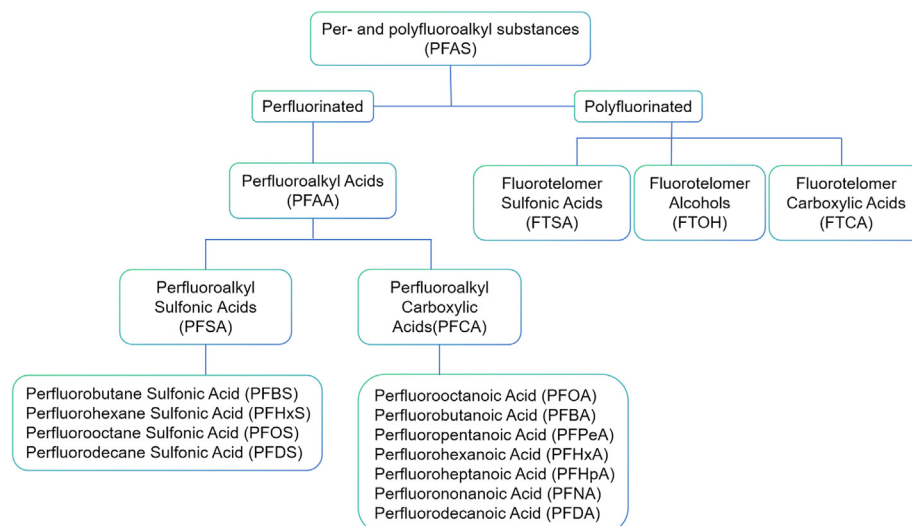
**Fig. 1.** Family tree of PFAS.

dimer acid (HFPO-DA), perfluorononanoic acid (PFNA), perfluorinated carboxylic acids (PFCA), perfluorohexane sulfonic acid (PFHxS), and perfluorohexanoic acid (PFHxA). PFAS in drinking water sources are a serious problem. Recently, a study reported PFAA and fluoroethers as major PFAS in the Cape Fear River, a drinking water source in California, USA [8]. The study was conducted from 2018 to 2021, which revealed an average of 3.4 kg/day of PFAS passing the river to enter the coastal marine water, putting about 1.5 million of the North Carolina population at risk. Rivers and groundwater along the Ganges River in India were examined to underscore PFAS content [9]. This study detected 15 PFAS, with the dominant being PFHxA (0.4–4.7 ng/L) and PFBS (<MQL to 10.2 ng/L), respectively, with short-chain PFAS being the most prevalent. Recently, PFAS were reported in untreated and processed drinking water samples collected from 18 water treatment plants in the Netherlands [10]. The water samples were classified into surface water and groundwater samples to better understand the distribution of PFAS in the collected samples from the treatment plant. The short-chain PFAS (300–1,100 ng/L) were the dominant group reported in the studied samples.

Studies have shown PFAS to be detrimental to human health and environmentally unfriendly [1], which indicates the importance of getting rid of them in water. However, they must be adequately detected and quantified before developing techniques for their removal in aqueous systems. Methods are being improved for rapid and adequate quantification of PFAS in water, especially the quantification of the -fluoro-species formed during water purification. Unfortunately, it has been discovered that PFAS are not completely removed from water by many of the wastewater treatment techniques [11]. Presently, there is still much to learn about the potential long-term effects of PFAS on both humans and the environment; the health risk linked to human exposure to PFAS is a serious concern. In many developed countries, a lot of studies have been conducted on the environmental impact assessment of PFAS to understand its fate and distribution with significant political and scientific attention. Though the situation is different in developing countries, such as those that are lagging behind in science and technology, there have been increasing efforts from a few countries in Asia and South America [12]. The information from many of the developing nations is still scant, and there is a need to assess the current PFAS status for better understanding. Therefore, this review aims to discuss the emergence of PFAS in water, health concerns, and their removal from water systems in developing nations.

## 2. Emergence and quantification of PFAS in the environmental water sample

### 2.1. Emergence of PFAS in water system

The emergence of PFAS in drinking water may be traced to point and nonpoint sources. Due to the fact that environmental chemical pollutants can decompose to generate stable PFAS under specific environmental circumstances they may act as chemical precursors for PFAS [13,14]. Several research investigations have shown that one of the sources of PFAS in surface water is drinking water treatment plants (DWTPs) or wastewater treatment plants (WWTPs) [15]. Moreover, the introduction of PFAS in environmental drinking water sources has been attributed to the discharge activities of sludge emanating from WWTPs or DWTPs into surface water without adequate treatment because a few of the decontamination steps may lead to the generation of PFAS [16]. Many WWTPs cannot completely remove PFAS or reduce it to the barest minimum, which may be considered insignificant. Many studies have confirmed this by detecting PFAS in tap and bottled drinking water. For example, a study investigated PFAS in 101 bottled water for sale in the US, revealing the presence of 15 PFAS (0.17–18.87 ng/L) consisting of C3–C10 PFCA, and C3–C6 and C8 PFSA [17]. Recently, 35 PFAS with concentrations ranging from 3.30 to 32.00 ng/L were detected in tap water samples collected from 42 locations in Barcelona [18]. The drinking water samples collected across 16 states in the US were analyzed to detect and quantify the presence of PFAS [19]. The results confirmed 26 unique PFAS in the analyzed water samples, with concentrations ranging from 1.90 to 234.50 ng/L. A study focusing on a small community in Alaska (Gustavus), US, studied drinking water from Gustavus residents for PFAS [7]. The study detected 14 PFAS from the collected water samples, including PFCA, PFSA, and fluorotelomer sulfonate (FTS), with concentrations ranging from undetected (ND) to 120 ng/L. Table 1 shows the detection of PFAS in tap and bottled water from some developing countries. The contamination is as high as 200 ng/L in tap water and 15 ng/L in bottled water. However, there is more information on PFAS contamination of surface water systems than on tap and bottled water in developing countries. The contamination of drinking water by PFAS is a global problem requiring urgent attention because of some of the associated health concerns. Many studies have been conducted in developed countries investigating end-used tap and bottled water to understand the quantity reaching final consumers; for example, bottled spring and

**Table 1**
Detection of PFAS in tap and bottled water from some selected developing countries.

| Country | Source | Sampling year | Concentration (ng/L) | Reference |
|---------|--------|---------------|----------------------|-----------|
| Brazil | Bottle water | 2014 | ND–15.00 | [20] |
| Turkey | Bottle water | 2017–2018 | 0.08–0.90 | [21] |
| Ivory Coast | Bottle water | 2015–2016 | 3.00 | [22] |
| Ghana | Tap water | 2015 | 197–200 | [23] |
| India | Tap water | 2006–2008 | <0.083 | [24] |
| India | Treated water | 2022–2023 | 20.40–48.71 | [25] |
| Turkey | Tap water | 2017–2018 | 0.08–11.27 | [21] |
| Vietnam | Tap water | 2014–2015 | 0.00–1.19 | [26] |
| China | Tap water | 2015 | 1.40–175 | [27] |
| Brazil | Tap water | 2014 | ND–28.00 | [20] |
| China | Tap water | 2021 | 1,490–2,150 | [28] |
| China | Tap water | 2018–2019 | 4.59–365.04 | [29] |
| China | Tap water | 2002–2006 | <0.10–45.90 | [30] |

ND, non-detectable; PFAS, per- and polyfluoroalkyl substances.

natural mineral waters collected from France were analyzed, which revealed 10 PFAS (PFOS, PFHxS, and PFBS) in 40 brands of bottled water [31]. Studies in this direction are minimal in developing countries, which suggests the need for further investigations to understand the amount of PFAS that gets to the final consumers of bottled water and tap water in such countries. This understanding will also help project the health

hazards that may have on the populace over a period of ingestion and bioaccumulation.

Studies have shown a widespread detection of PFAS in drinking water and drinking water sources from Europe, the Americas, Asia, and Australia [32]. Presently, information on PFAS from Africa is limited due to the inaccessibility of research facilities for routing environmental studies to monitor PFAS. However, PFOS, PFPeA, PFOA, PFHxA, and perfluorodecanoic acid (PFDA) were reported in drinking water and rivers in Ghana [24]. Table 2 presents some dominant PFAS detected in drinking water sources in several developing countries. The reported concentrations vary across sources, suggesting pollution of both surface and ground water systems. Data emanating from bottled and tap waters studied in Burkina Faso and Ivory Coast showed the presence of PFAS in samples collected from different locations [23]. Sediments and the river from the Vaal River revealed the presence of 15 PFAS, with PFOS being the most frequently detected from the studied sites [33]. Niger River in Mali (4.7 ng/L) and the Sabaki River estuary in Kenya (4.6 ng/L) were reported to be contaminated with PFOS [34]. A similar observation was reported from surface water samples collected from Nigeria, Egypt, Morocco, the Congo, Kenya, and Mauritius [35]. Many European countries have documented the occurrence of PFAS in surface water and commercially available drinking water [32]. The Mediterranean Rivers [36] and the Llobregat and Jucar Rivers in Spain [37,38] have been reported to be contaminated with PFAS. Similarly, PFAS has been reported in rural areas far from urban and industrial areas, suggesting the

**Table 2**
Dominant PFAS detected in drinking water sources in selected developing countries.

| Country | Source | Dominant PFAS | Concentration (ng/L) | Year | Reference |
|---------|--------|---------------|----------------------|------|-----------|
| India | Surface water and groundwater | PFHxA | 0.40–4.70 | 2014 | [9] |
| | | PFBS | <MQL–10.20 | | |
| | | PFBA | <MQL–9.20 | | |
| | | PFBS | <MQL–4.90 | | |
| India | Surface water | PFOA | <1.50–24.80 | 2018–2019 | [39] |
| | | PFOS | <1.20–13.90 | | |
| Kenya | Lake Victoria Gulf | PFOS | <0.40–2.53 | 2006–2007 | [40] |
| | | PFOA | <0.40–11.70 | | |
| Brazil | Surface water and groundwater | PFOA | 11–718 | | [41] |
| | | PFOS | | | |
| | | PFHpA | | | |
| Bangladesh | | FTOHs | <LOQ–19 | 2020 | [42] |
| | | PFBA | | | |
| South Africa | Vaal River | PFBS | <LOQ–24.70 | 2014 | [33] |
| | | PFHxS | <LOQ–7.60 | | |
| | | PFOS | 0.40–35.70 | | |
| | | PFHxA | <LOQ–20.30 | | |
| | | PFOA | 0.60–4.60 | | |
| | | PFNA | <LOQ–1.80 | | |
| Mexico | Groundwater and surface water | PFBS | 0.91–155.40 | 2020–2021 | [43] |
| | | PFPeA | | | |
| | | PFHxA | | | |
| Nigeria | River | PFOS | 3.90–10.10 | 2016 | [44] |
| | | PFOA | 0.80–2.80 | | |
| Ethiopia | Lake Tana | PFOS | <0.05–0.22 | 2014 | [45] |
| | | PFOA | <0.28–0.69 | | |
| South Africa | Plankenburg River | PFBS | <LOQ | 2014 | [46] |
| | | PFOS | <0.06–12.40 | | |
| | | PFBA | 10.20–28.40 | | |
| | | PFOA | 12.80–62.60 | | |
| | | PFNA | <LOQ | | |
| Ghana | Pra and Kakum River | PFOS | 77.20–277.00 | 2015 | [24] |
| | | PFOA | 1.78–321.00 | | |
| Uganda | Lake | PFOS | 1.60 | 2015 | [47] |
| | | PFOA | 2.40 | | |
| Mexico | Wastewater treatment plant | PFBA | 176.9 ± 3.3 | 2019 | [48] |
| | | PFHxA | 133.4 ± 2.5 | | |
| | | PFHpA | 116.6 ± 3.9 | | |
| | | PFOA | 133.1 ± 3.5 | | |
| | | PFUnA | 23.5 ± 6.5 | | |

FTOHs, fluorotelomer alcohols; LOQ, limits of quantification; PFHxS, perfluorohexane sulfonic acid; PFHxA, perfluorohexanoic acid; PFBS, perfluorobutane sulfonic acid; PFNA, perfluorononanoic acid; PFDoDA, perfluorododecanoic acid; PFDA, perfluorodecanoic acid; PFBA, perfluorobutanoic acid; PFPeA, perfluoropentanoic acid.

extensive impact of PFAS on environmental water systems, which shows the need for a detailed understanding of the fate of PFAS in the environment.

A study in the Middle East revealed the presence of PFAS in Saudi Arabian coastal waters, detecting the presence of 12 PFAS in surface water up to 956 ng/L [49]. Saudi Arabia is the largest producer of desalinated water, and the presence of PFAS in drinking water is a challenge to the supply of safe drinking water in Saudi Arabia and many other Middle East countries. Fish samples collected from the Saudi Arabian Red Sea have shown the presence of PFAS; however, effluents from the WWTPs are reported to be the main contributor of PFAS to the Saudi Arabian biota [50]. There is scant information on the assessment of PFAS in water systems in the United Arab Emirates (UAE). Although there are published articles on other groups of water pollutants in UAE waters, but information on PFAS environmental contamination is scarce. This is also the case for many Middle Eastern countries. Recently, PFOS and PFOA were detected in water samples collected from the Karun River in Iran [51]. Similarly, PFAS have been detected in wastewater-irrigated farmland in Jordan [52]. A similar situation also existed in Turkey, with the detection of PFAS in tap and bottled water samples [22]. PFAS was reported in human serum and milk collected from patients in Lebanon involving 419 pregnant women, which may be linked to exposure to PFAS-contaminated drinking water [53]. Unfortunately, no serious monitoring has been documented for water systems from Kuwait [54]. Many countries in South America and the Caribbean have reported the detection of PFAS in surface water within the region [32]. The large-scale production and frequent use of PFAS-based pesticides in many South American countries have contributed to its environmental presence. These pesticides include sulfluramid, which contains ethyl perfluorooctane sulfonamide, a PFOS precursor [55,56]. Brazil is a major importer of sulfluramid to neighboring South American countries; a study reported that this activity within the years 2004–2015 could presumably contribute to the release of about 167–487 tons of PFOS/FOSA (perfluorooctane sulfonamide) into these South American environments [57]. When ethyl perfluorooctane sulfonamide gets into the environmental water system, it adsorbs into the sediment and converts to PFOS and FOSA. PFOS, and FOSA in ecological water systems (surface water and groundwater) studied in Brazil and Columbia have been linked to using sulfluramid pesticides [55,57].

Although there is a need for extensive study, a lot of efforts have been made to understand the fate of PFAS in the Asia–Pacific region. A study conducted in the Philippines, China, Thailand, and Japan revealed that the concentration of PFOS ranges from ND to 54 ng/L [32,58]. The concentration varied due to the choice of sampling location, data variability, and analysis method. Recent studies have shown the concentration of PFOS and PFOA from some sites studied in China to be in trace levels, such as 0.013 ng/L [59,60], while some other studies reported concentrations up to 1,590 ng/L [60–63]. A study evaluated PFAS in rivers, drinking water sources, and various drinking water types in Qingdao, eastern China [64]. The study revealed that the concentration of PFAS in the river ranged from 28.3 to 292.2 ng/L, while that of tap water ranged from 20.5 to 29.9 ng/L. The study suggested a high level of PFAS loading in the suburban and rural rivers, which reflects the anthropogenic activities, and further estimated an annual PFAS loading of 5.9 t to Jiaozhou Bay. Although the concentration of the drinking water reservoir is lower than that of the river, achieving a complete removal of PFAS would not be a bad idea for water consumers in the city of Qingdao. An evaluation of the Indian River Lagoon and the Atlantic coast within Brevard County, Florida, revealed the presence of PFBA, PFBS, PFHxA, PFOA, PFDA, and PFOS [65]. Surface water samples collected were analyzed for 92 PFAS. Among the sites studied, the Banana River demonstrated the highest concentration of PFAS. PFBA, PFNA, and PFOA were found in 16 samples collected from the Periyar River with concentrations of PFBA between 58 and 2,174 ng/L, PFNA between 20 and 705 ng/L, and PFOA between 22 and 1,503 ng/L [66]. The Periyar River was chosen because it is the most contaminated

flowing river in Kerala, India. As a flowing river, the concentration of PFAS was highest at the estuary, where PFOS concentration was reported to be 12,958 ng/L, attributed to contributions from industrial emissions emanating from nearby industries.

Apart from China, many of the developing countries in Asia, Africa, Europe, the Middle East, and North and South America need to conduct more studies to understand the distribution and fate of PFAS in environmental water systems as well as in drinking water supplies. The current information is scant, making it difficult to draw a logical conclusion in many countries. Compared to studies conducted on PFAS from the US, the United Kingdom, Germany, Japan, Canada, and other developed countries, information from most developing countries lacks depth and richness. The US has evaluated national data sets to gain insight into the concentration, sources, and composition of PFAS in drinking water [67], tremendous efforts have been put into developing national guidelines for handling PFAS [68]. In many European countries, efforts are ongoing to develop regulations for managing the emissions of PFAS, and there are established requirements for monitoring PFAS in drinking water [69,70], which are not available in most developing countries due to a lack of sufficient data set. This shortcoming calls for more research to help improve drinking water quality. While surface water remains the primary drinking water source in many nations, using recycled wastewater as a drinking water source is also promoted. Unfortunately, the PFAS in both recycled wastewater and WWTP sludge to surface water have negatively affected the use of these drinking water sources in many developing countries. Many personal care products, firefighting foams, textiles, aviation hydraulic fluid, electronics, protection nonstick coatings, and other consumer goods, have contributed to the release of PFAS into the environment [32]. Perfluorinated compounds are highly stable and difficult to degrade due to the magnitude of the C–F bonds that occur in their structures; however, partially fluorinated groups are less stable due to the low amount of the C–F bonds, permitting some level of degradation when mitigated. Such mitigation may lead to stable perfluorinated moieties, sometimes called precursor molecules for PFAS [71].

## 2.2. Quantification of PFAS in water sample

The detection and quantification of all known PFAS in matrix samples remains challenging, with only a limited number being adequately quantifiable using the analytical methods available [72]. The known analytical methods for monitoring PFAS and their precursors in drinking water systems rely on reference standards and isotope-labeled internal standards. The lack of sufficient PFAS standards has limited the detection and quantification of PFAS. Many known methods for sample preparation for analyzing, identifying, and quantifying PFAS require improvement. The sample pretreatment and extraction of PFAS from the sample matrix are achieved by solid-phase extraction (SPE) and may require an ion exchanger and elution with the most efficient solvent system. Several methods have been developed for PFAS analysis; for example, the standard DIN 38407-42 method of analysis with a lower limit of quantification (LOQ) is adequate for specific PFOA and PFOS with a LOQ of 10 ng/L [73,74]. However, with recent advancements, a LOQ of 1 ng/L is attainable with newly improved laboratory methods of analysis [72], most of which can quantify both short- and long-chain PFAS. The ISO 21675 demonstrates a LOQ of 0.2 ng/L, standing out for its low LOQ for analysis of 20 PFOA and PFOS with carbon chain lengths ranging from 4 to 13 atoms, which qualify the method as drinking water directives for the European Union (EU) [75–77].

The EN 17892 method, a European standard for PFAS in drinking water, was published by the Technical Committee on Water Analysis of the European Committee for Standardization (CEN), validating it for the analysis of 9 PFAS in drinking water [32]. However, there is a need to validate the application of the method for surface water and groundwater. Some selected analytical methods for analyzing PFAS in the complex matrix are presented in Table 3 [78–83]. Method 537.1 is a modification of

method 537 [78]. The method uses SPE and liquid chromatography--tandem mass spectrometry (LC–MS/MS) and is suitable for analyzing PFAS in drinking water at low ng/L. The method has been successfully used to monitor PFAS with high sensitivity in drinking water. Method 533 relies on isotope dilution ion exchange SPE and LC–MS/MS for the analysis of PFAS [79]. Many other methods are on the draft waiting list for validation. The U.S. Environmental Protection Agency (EPA), in collaboration with other agencies and departments, has published many draft methods that can help identify PFAS in water; Method 1633 can identify about 40 PFAS in landfill leachate, surface water, and groundwater, wastewater, and soil samples [80]. The EPA's analysis methods are meant to achieve analytical accuracy and precision. Many methods have also emerged [81]. There are hundreds of PFASs with different carbon chain lengths. Therefore, there is no single method of analysis that can cover all PFAS known. Two or more analytical methods might be combined to achieve wider identification and quantification of PFAS. There is a need to develop a comprehensive analysis method.

Some challenges arise during the quantification of PFAS in drinking water. For example, PFAS may adsorb on the walls of containers for bottled water, especially in the case of plastic or polymer containers. This observation may be associated with the functional groups present in PFAS, such as PFBS, PFOS, PFOA, PFBA, etc. Selecting a method for total organofluorine (TOF) in water depends on selectivity and inclusivity because it is necessary to remove fluoride interferences during analysis. When the technique is too inclusive, it does not help differentiate between organic and inorganic fluoride, which makes it difficult to estimate and quantify PFAS-related TOF in drinking water samples. There is no standard analytical method recommended for estimating TOF in a drinking water matrix. However, since other sources have no interferences, TOF can be easily quantified if the component PFAS is known in a simple single-PFAS water sample. Methods such as the extractable organofluorine (EOF) and adsorbable organofluorine (AOF) techniques are well-known [84–87].

## 3. Regulation and guideline for PFAS in water

Due to the health challenges associated with PFAS, it is crucial to regulate and develop guidelines for handling them. Unfortunately, this is affected by analytical detection and social, economic, and political influences [88,89]. Several reports have indicated the need to set guidelines for PFAS. The persistence and bioaccumulation of PFAS have been reported in blood [90,91], drinking water, and some other foodstuffs [92–94]. PFAS can bioaccumulate in the human body more than most known water contaminants and have high health consequences even at low concentrations. PFAS has been a subject of discussion in the Stockholm Convention to monitor the impact of organic pollutants on human health and the environment. The EU regulation (2020/784) that amends the restriction on PFAS considered the use of PFOA and related

compounds, which sets a maximum concentration of 0.025 mg/kg for PFOA while the maximum concentration for its related compounds was set at 1 mg/kg [94,95]. All plans to phase out the use of PFOS, PFOA, and their precursor molecules failed; therefore, the EPA made an effort to draft update values for PFOS (0.02 ng/L) and PFOA (0.004 ng/L) and set PFBS and Gen-X at 2,000 and 10 ng/L, respectively [88,96,97]. Interestingly, the National Health and Medical Research Council of Australia set a limit of 70 and 560 ng/L for PFOS + PFHxS and PFO, respectively [98,99]. Other countries, like Canada [32,100], Italy [32,101,102], Sweden [103,104] and Denmark [32,105] have made considerable progress. However, many developing countries do not have national guideline levels for PFAS in water.

The EPA has not established any national drinking water standards for PFAS. However, in 2016, the EPA finalized a nonregulatory advisory of 70 ng/L for PFOA and PFOS [106]. Some states in the US, such as Minnesota [32,107], New Jersey [32,108], Michigan [32,109,110], New York [32,111,112] and California [113–115] have set thresholds as guidelines for PFOA and PFOS. Due to the concern and urgency to regulate PFAS in water, some US states have proposed guidelines for drinking water sources (surface and underground water systems) based on health challenges [116–119]. The use of long-chain PFAS is discouraged, and manufacturing industries are mandated to declare the type and concentration of PFAS used during the production process for regulatory purposes [88,117,120,121]. Effluents emanating from these industries must be treated to reduce PFAS load; unfortunately, there are no standards to ensure conformity among these industries. The EPA has tried to develop guidance levels but has not for drinking water permissibility levels [120–122]. The EPA reported a health advisory level for PFOA (0.004 ppt), PFOS (0.02 ppt), Gen-X (10 ppt), and PFBS (2,000 ppt) [32, 123]. It is essential to set a global standard that can help the world. The long-chain PFAS are highly bioaccumulative in humans, many of which are lipophilic [106]. In principle, water guidelines are developed based on toxicity and exposure factors. However, this takes time and continuous research effort with financial commitment. Most states in the US depend on animal toxicological data to develop their current guidelines for PFOA and PFOS at state levels. In contrast, the risk assessment is generally based on nonthreshold assumptions [92,106,124,125]. Many developed countries manage PFAS by limiting their use in everyday products, monitoring occurrence, and developing guidelines for handling and processing. Most of the least developed countries rely on EPA guidelines for operations, and some even adopt EPA standards for regulating drinking water contaminants as their national standards. Consequently, it is essential for governments to invest more in scientific development and activities that promote the capacity to establish drinking water standards and effectively regulate water contaminants.

Previously, the EU published a document on the commercialization and production of PFOS and its derivatives [126,127], superseding the Regulation (EU) 2019/1021 [127,128]. The EU made several

**Table 3**
Selected analytical methods for PFAS quantification in water sample.

| Method | Comment | Reference |
|---|---|---|
| Method 537.1: determination of selected PFAS in drinking water by SPE and LC–MS/MS | Measures PFAS in drinking water using solid phase extraction and LC–MS/MS at low ng/L. It can detect and measure the short-chain PFAS in water, including the Gen-X groups. | [78] |
| Method 537: determination of selected PFAS in drinking water by SPE and LC–MS/MS | The method can detect and measure selected PFAAs in water by SPE extraction and LC–MS/MS | [82] |
| Method 533: determination of PFAS in drinking water by isotope dilution anion exchange SPE and LC–MS/MS | The method targets short-chain PFAS (C1–C12 only). This includes fluorotelomers, sulfonates, poly/perfluorinated ether carboxylic acids, PFAAs, and sulfonates. | [79] |
| Method 8327: PFAS using external standard calibration and MRM LC–MS/MS | The method makes use of LC–MS/MS for detection and quantification of PFAS. | [83] |
| Draft method 1633 and 1621 | The method can test up to 40 PFAS compounds in wastewater, surface water, groundwater, soil, biosolids, sediment, landfill leachate, and fish tissue. | [80] |
| SW-846 test method 0010: modified method of analysis | The method is good for semi-volatile PFAS. It uses an isotope dilution train approach for GC–MS targeted and nontargeted analysis. | [81] |

PFAAs, perfluoroalkyl acids; SPE, solid-phase extraction; LC–MS/MS, liquid chromatography/tandem mass spectrometry.

interventions, with the conclusion that the impact of derivatives of PFOS and PFOA is not well understood, which suggests the need for more studies to enhance the development of an all-encompassing or well-informed regulation [129]. In 2019, the Norwegian Environment Agency put forth a proposal to the Stockholm Convention, recommending the inclusion of PFHxS and its derivates on the list of persistent organic pollutants [127]. Interestingly, with the development of technology to determine PFAS at low concentrations, the European Commission proposed the ban of all PFAS in firefighting foams across the EU, which led to the assessment by the European Chemicals Agency (ECHA) on the risk and possible strategies [130,131]. The proposal further prohibits using, marketing, formulating, or compounding any form of PFAS in industrial or commercially available products [132]. Many other European countries have also submitted proposals to ECHA, but efforts are ongoing to bring these into comprehensive and enforceable legislation.

The US and Canada have made remarkable efforts to protect the environment from the negative impact of PFAS. The US federal government and state legislatures have covered many grounds in developing guidelines for some states through the support of the EPA. For example, in 2021, the EPA announced the PFAS strategy roadmap, which was a success in helping and safeguarding communities in the US from PFAS contamination [133,134]. In 2023, the EPA developed national drinking water regulations establishing maximum levels for PFNA, PFBS, PFOA, Gen-X, PFOS, and PFHxS [127]. Furthermore, with the support of the EPA, lawmakers have enacted more than 250 PFAS-related bills to monitor and regulate their maximum levels. In South America, Brazil has made tremendous efforts to control the contamination by PFAS in the environment, and many of these initiatives are still ongoing [135,136]. In Asia, China is leading in the fight to eradicate PFAS, and has put 18 PFAS on the list of priority control chemicals [127]. Japan, Thailand, India, Vietnam, Indonesia, and Singapore are also making efforts. In 2022, Vietnam listed PFAS on the drafted Decree No. 82/2022/ND-CP as chemicals to be regulated [127]. Africa is behind in setting guideline levels for PFAS in water. However, many African countries endorsed the Stockholm Convention to develop national implementation plans but failed to include PFAS in their national implementation plans [137,138]. Africa needs to catch up with efforts from other regions of the world, and African countries need to do more by investing resources in eliminating PFAS in environmental water systems.

Many developing countries are not encouraging, and the efforts directed toward developing regulations for the provision of clean drinking water are poor. It is important that governments in developing countries promote and fund initiatives that ensure the enactment of policies supporting the provision of clean drinking water free of PFAS. Among the developing countries, the BRICS (Brazil, Russia, India, China, and South Africa) are the financially and scientifically strong countries that may help support other developing countries by driving initiatives and policies aimed at achieving SDG 6 for the provision of clean drinking water. The BRICS may need to enhance scientific development by promoting activities that will fund scientific exchange programs or initiatives where the stronger developing countries can help the least developed through knowledge transfer, skill acquisition, and funding of scientific activities. In fact, there is a need to support collaborative research and guidelines for policy formation to assist the least developed countries. Governments in developing countries need to strengthen their political will to abide by the Stockholm Convention and invest more in monitoring regulated and unregulated water pollutants. There is an urgent need to support and strengthen government agencies saddled with the responsibility of environmental monitoring and impact assessments. The governments in many developing countries need to work-the-talk by investing in education, research, and development. It is also important to develop locally sourced or invented strategies for managing PFAS contamination in water. Such strategies should be indigenous for sustainability and easy management instead of embracing techniques that are expensive for developing countries to sustain. A strong and unwavering regulatory framework will help developing countries because, if

the framework is enforced, the pollution can be easily managed, reducing spending on treatment.

## 4. Health effects of PFAS contaminated water

Most studies on the toxicological effects of PFAS focused on PFOA and PFOS. PFAS is widely used, and it was not until a few years ago that its health challenges were considered a problem. Production and distribution of PFOA and PFOS have been discontinued in many nations, but they continue to be detected in the blood of human beings [139]. The presence of PFAS in drinking water may lead to high cholesterol levels, hormonal disruption, testicular and kidney cancer, high blood pressure, and a decrease in vaccine potency in children [140–142]. PFAS at trace doses are unhealthy, which may affect immune and metabolic systems [143–145]. Unfortunately, only a few PFAS are studied to understand their toxicity profile. Their interactive mode, half-life, absorption, and long-term toxicity effects are little known. More attention must be given to understanding the toxicity profile of the unavoidable or essential PFAS class to understand better how to handle them for safety when used in industrial products. Some studies have revealed that PFOA may cause testicular and kidney cancer [146–148]. Studies have shown that the currently promoted short-chain PFAS (Gen-X) used as a replacement for the discontinued PFAS is also becoming environmentally unfriendly, and studies have revealed bioaccumulation in humans with possible health adverse effects [149–152]. This situation has become worrisome, suggesting the need to regulate PFAS, especially in drinking water.

PFAS health-related challenges are a serious concern, and care must be taken in handling the devastating effect this may have on the public health. A study on the level of PFAS in blood demonstrated that PFAS can contaminate the human system [153]. The study was conducted in Europe, using 1,957 children and teenagers as participants, and all the samples tested positive for PFNA, PFOS, PFHxS, and PFOA. Unfortunately, there are challenges in assessing the information needed to understand the toxicological impact of PFAS because several hundred PFAS and their derivatives are known, making it difficult to screen them all. Furthermore, the chemical nature and structures of their derivatives are limitations to studying these PFAS, as they can be metamorphosed into derivatives under different environmental conditions. PFAS are absorbed in the gastrointestinal tract and can bind to blood serum protein to be transported to organs in the human body [154,155]. A study has revealed that PFOS and PFOA may have a half-life of up to 5 years in the human body [156]. The carbon chain length of PFAS was reported to be inversely proportional to its elimination from the human body [157]. Even though the short-chain PFAS are known to bioaccumulate less than the long-chain moieties, the bioaccumulation of Gen-X and ADONA (dodecafluoro-3H-4,8-dioxanonanoate) are not well understood, and there is a need for more research to be conducted in this regard [158,159]. Recent studies have revealed placental abnormalities in mice treated with Gen-X with reduced thyroid hormone and elevated peroxisome proliferator-activated receptors (PPAR)-regulated gene expression levels in the livers [160–162]. While a birth defect was reported with F-53B in zebrafish [163], a study by Gaballah et al. [164] revealed no toxicity. Other studies have shown converse results to reports of established toxicity with short-chain PFAS; such conflicting conclusions call for more studies to understand the actual hazards associated with the short-chain moieties.

Data on the composition and processing conditions of products containing PFAS are kept confidential by business owners, making it difficult to follow through on the chemical characteristics of PFAS and possible changes in structure that may have occurred through product formation. Many animal studies are taking a turn from rodents to zebrafish as models for the toxicological study of PFAS. A few of the studies leveraged immune suppression, hepatic/lipid metabolic toxicity, tumor induction, obesity, developmental toxicity, and endocrine disruption [165]. Apart from the danger associated with long-chain PFAS, the Gen-X group has shown an alteration in liver function, leading to apoptosis in mice and fish [162,166]. The review revealed the need for more studies on the

short-chain PFAS groups to understand their safety profile. Studies have shown that long-chain PFAS are contaminants of high concern because of the health hazards associated with their presence in the human body [167]. Therefore, it has become necessary to replace them, although the replacement process is not straightforward [150,168]. Although short-chain PFAS has received attention as a promising replacement, recent studies are indicating possible hazards for humans from the use of short-chain PFAS [165,169,170]. This revelation suggests the need for more studies to be conducted in this area. The fate of long-chain and short-chain PFAS under environmental conditions in many developing countries is not well understood due to a lack of monitoring evaluation. This makes it difficult to know the possible transformation that may occur to PFAS under the environmental conditions in the countries. Previous studies showed dysfunctional mitochondria in mice [171], with steatosis being a common feature [165,172]. Despite the understanding of the health hazards of PFAS, details on the mode of action of PFAS in the human body are not known to date. However, a few studies have linked this to the activation of some nuclear receptors such as PPARβ/δ, liver X receptor α, Erα, PPARα, CAR, PPARγ, and pregnane X (PXR) [173–176]. There is a need to conduct more studies that will involve changing the process parameters in exposure to PFAS; this may include the time of exposure, dose-dependent study, the effect of animal sex, etc., to have a better understanding of the mode of action and adaptation strategy of the animals being studied in the *in vivo* experiment.

## 5. Removal of PFAS from water

Many techniques have been reported for removing PFAS from water systems [177,178]. The strong C–F bond makes many of these techniques, such as flocculation, biodegradation, sedimentation, oxidation, and disinfection, inefficient for the removal of PFAS from water [11,179,180]. Many known conventional water treatment methods cannot completely remove PFAS from water because of their high structural stability. Membrane technology, photocatalysis, and adsorption are promising technologies for achieving the removal of PFAS in water. A few studies have combined separation and destruction techniques to remove PFAS from the water system. The separation techniques include the use of adsorption, ion exchange, and membrane techniques, while the destruction techniques make use of thermal destruction, advanced oxidation processes,

electrochemical oxidation, and advanced reduction [181–188]. The merits and demerits of some of the selected techniques for removing PFAS from water systems are compared in Table 4 [183,189–206].

The adsorption techniques using activated carbon and other materials as adsorbents have shown encouraging success. The technique is suitable for low concentrations of PFAS and can efficiently remove the long-chain PFAS from water systems; however, the poor regeneration capacity of most of the reported adsorbents is a challenge [189–192]. Many low-cost adsorbents have made the technique cheap and affordable. Still, competing interferences in a complex matrix water sample hamper the technique's performance due to challenges from selectivity and low uptake of PFAS from complex matrix systems. The cheap and abundant availability of biobased materials in developing countries makes adsorption a suitable option for the removal of PFAS from water systems. A few research works from developing countries have focused on the use of bio-sorbents for this purpose. A good example is the study on biochar filters as complements for sand filters for removing PFAS from water [207]. Many such studies have been conducted by scientists from developing countries in developed countries with the hope of acquiring skills to help developing countries. The membrane technology is outstanding for treating complex matrices of water systems, making it suitable for municipal use. The membrane technique can sufficiently handle short- and long-chain PFAS in the water system. In the case of a complex polluted water matrix, it can efficiently remove inorganic and organic pollutants in water. However, the performance of membrane technology is hampered by fouling, which is a significant challenge to this technique [190,197–200]. Furthermore, the process may become expensive due to high-pressure requirements and energy costs. The ion exchange technique suits ionic and long-chain PFAS at low concentrations. Unfortunately, it is also inefficient for complex mixed matrices of water samples. When completely spent, replacing or regenerating the resin may increase process costs.

The photocatalytic process is destructive, and PFAS cannot be reconcentrated at the end of the removal process because they are converted to smaller molecules like $CO_2$ and $H_2O$. The photocatalytic process is suitable for low concentrations of PFAS. One advantage of the process is that the energy bandgap required for the photodegradation can be modified to suit the light range needed for the process; unfortunately, one of the major challenges of the photocatalytic process is the

**Table 4**
Merit and demerit of some selected techniques for treating PFAS-contaminated water system.

| Merit | Demerit | Reference |
|---|---|---|
| *Adsorption: powder (PAC) and granular (GAC) activated carbon* | | |
| I: Can efficiently remove PFAS from water even in the presence of other contaminants. | I: May exhibit poor regeneration capacity, which makes it expensive to reuse. | [183,189–192,193–196] |
| II: Nondestructive, good for low concentrations (ng/L) of PFAS in water. | II: Cannot efficiently remove short-chain PFAS from water due to weak hydrophobic interaction. | |
| III: Can efficiently remove long-chain PFAS from water. | III: Performance may be hampered by the presence of organic molecules. | |
| IV: Relatively affordable. | | |
| *Membrane filtration* | | |
| I: Very efficient for mixed matrix contaminated water treatment. | I: Fouling is a major problem that can reduce performance. | [190,197–200,201] |
| II: Can efficiently remove both short and long-chain PFAS from the water matrix. | II: High energy may be required, which increases process cost. | |
| III: Nondestructive, efficient for the removal of both organic and inorganic water contaminants. | III: In some cases, membrane regeneration may be expensive, which increases process cost. | |
| IV: Water purification can be achieved within a short time with high performance. | | |
| *Ion-exchange separation* | | |
| I: Can efficiently remove ionic and long-chain PFAS at low concentrations. | I: Less efficient for mixed matrix contaminated water treatment. | [190,192,194,202–204] |
| II: Exhibits higher performance than the use of activated carbon. | II: Not efficient for short-chain PFAS. | |
| III: Cheaper operating cost than the use of activated carbon. | III: Resin regeneration for reuse is expensive. | |
| *Photocatalysis* | | |
| I: Efficient for low concentration, photostability, fast electron transfer. | I: Fast recombination of photogenerated charge carriers is a destructive process. | [205,206] |
| II: High surface area to volume ratio and rapid diffusion rate. | II: Cytotoxicity might be a problem. | |
| III: Improved degradation efficiency. | III: Agglomeration might be a challenge. | |
| IV: Absorbs visible light and controllable bandgaps. | IV: Toxicity and poor recovery from water sample. | |

recombination of the electron $(e^-)$/hole $(h^+)$ pair [205,206]. It is essential to note that when a complex matrix of highly polluted water such as municipal wastewater, landfill leachate, or industrial wastewater is to be treated, it is paramount to conduct a pretreatment on the wastewater to be purified to ease PFAS removal [208].

Efforts are ongoing to develop sustainable and efficient methods for the removal of PFAS from water. WWTPs are one of the contributors of PFAS to environmental drinking water sources in developing countries. Most WWTPs in developing countries cannot efficiently remove PFAS from wastewater because many of them were not designed to cater to PFAS in water. Many water corporations and water agencies in developing countries are trying to improve the capacity of their WWTPs to remove PFAS. The situation is very challenging in the least developed countries that do not have the financial capacity to purchase or develop new WWTPs in rural and urban communities to provide clean tap water. It is difficult to pinpoint the method for the removal of PFAS from water in developing countries because this information is not concisely available. Apart from the many innovative ways for removing PFAS from water published by authors from Asia [209–212], many other developing countries are still behind.

## 6. Current perspectives, cost evaluation, and future recommendations

Currently, the focus is on using short-chain and novel PFAS instead of long-chain moieties. More novel and short-chain PFAS are expected to be utilized under strict monitoring. Therefore, efforts should be made to better understand the fate and morphological changes that may occur by exposing these groups of PFAS to environmental factors. It is also vital to develop better and more rapid methods for detection, quantification, and treatment of these groups of PFAS in the water system. Most studies on PFAS in drinking water have focused on the target group of PFAS, with limited information on the other groups classified as nontarget PFAS. The most studied PFAS are PFOA and PFOS; however, more studies are still required on the nontarget group of PFAS, even though information on the short-chain and Gen-X is limited.

Ionic PFAS are rarely studied, despite the danger associated with them. It is necessary to study the nature of ionic PFAS in the environmental water system to understand the lower molecules they disintegrate into when exposed to environmental factors like temperature, pressure, etc. These lower molecules may have toxic effects. The ionic PFAS includes zwitterionic and cationic PFAS. Presently, there is no generally accepted standard analytical method of analysis for most ionic PFAS, including zwitterionic and cationic PFAS. This may be attributed to insufficient isotope-labeled analogs for electrospray ionization, ESI (+) PFAS, which is primarily problematic [89]. Proper identification of some PFAS is challenging because they may exist in different isomer forms. There is a need to have a priority list of PFAS identified in drinking water and its sources to ensure effective quantification and monitoring, which will aid in the development of allowable standards for global practice.

Adequate quantification of TOF in sources of drinking water, such as surface water and groundwater samples, is challenging and requires further investigation. TOF must be correctly evaluated for a comprehensive evaluation of PFAS in water to avoid doubt in interpreting the data. Combustion ion chromatography (CIC) has demonstrated low sensitivity toward organofluorines [89] and does not suggest the structure of the organofluorines, limiting the use of CIC for quantifying organofluorines in drinking water samples with low organofluorine content.

The lack of state-of-the-art equipment for the analytical evaluation of samples collected from different water sites in some developing countries is a setback for understanding the status of PFAS in such countries. There is a large data gap concerning the occurrence or status of PFAS in drinking water and environmental drinking water sources (including WWTPs, surface water and groundwater systems) in developing countries. Therefore, it is expedient for researchers in developed and

developing nations to collaborate to effectively understand the nature of PFAS in drinking water in science- and technology-lagging countries around the world. There is a need for water agencies and governments in different countries to increase funding for water studies to understand the occurrence and fate of PFAS in water. There is no sufficient data to establish the molecular interaction of PFAS in the human body. There are lots of questions to be answered. Unfortunately, data on the effect of short-chain PFAS on the human system are inconsistent [213], indicating that the threat of both long and short-chain PFAS is not entirely understood [145], suggesting the need for more studies to be conducted. It is difficult to completely rely on extrapolated data from the laboratory animal studies as a model for final human results; therefore, more data are required.

The cost evaluation of running the present techniques for removing PFAS from water is essential to understanding the feasibility and economic viability of the techniques. Treating PFAS-contaminated water systems is expensive. For example, Brunswick County, North Carolina, utilized reverse osmosis to treat the PFAS-contaminated Cape Fear River watershed, which cost $99 million and will require an annual expense of $2.9 million [214]. Different tools have been designed to estimate the cost of removing PFAS from water; many of these tools consider many inputs and outputs, which included the cost of infrastructure, consumables, labor, service fees, transportation, etc. Many have also applied to the EPA-derived work breakdown structure [215,216] to estimate the treatment cost, which covers derived system-level, add-on, indirect capital, administrative, and annual operation and maintenance costs. A study estimated the cost of purifying PFAS-contaminated water using GAC and ion exchange resin to establish economic sustainability [217]. The authors considered the initial flow rate for the treatment plant to be 0.740 million gallons/day and an initial concentration of PFAS to be $3 \times 10^{-3}$ mg/L while resin contact was 2 min/vessel. The direct cost of running GAC ($105,001) is double that of the resin ($52,248), suggesting the resin system is more economical. The study further considered the social cost of carbon concerning utilizing GAC and resin and found the total social cost of carbon for GAC ($6,966) is higher than that of the resin system ($4,332), which further buttresses the fact that the ion exchange technique is a cost-efficient technique when compared with GAC. A recently reported life cycle treatment cost for PFAS combined the EPA-derived work breakdown structure and the manufacturer price for adsorbent to arrive at an annual operation cost for GAC and ion exchange resin ($19,879). The study also confirmed the yearly cost of running GAC ($78,445) is higher than that of the resin system ($11,246) for removing PFAS in water [218]. Similarly, during an annual EPA meeting in 2020, the cost of running water treatment for PFAS removal using reverse osmosis, GAC, and ion exchange techniques were compared to provide PFAS-free water for over 2,000 households. The team gave an annual cost of $49,000,000, $48,000,000, and $50,000,000 for reverse osmosis, GAC, and ion exchange techniques, respectively [219].

The cost comparison for removing PFAS by GAC and ion exchange resin at a pilot scale was conducted in a continuous flow at a Bäcklösa DWTP in Uppsala, Sweden [190]. The cost comparison was based on 80% recovery, factoring in predetermined operation parameters such as particle filter replacement, energy, and cost of the antiscalant membrane. The annual operation cost revealed that the ion exchange resin sorption process is more economical than the GAC process. A landfill leachate in Thailand was investigated for its net present cost using a reverse osmosis membrane system to remove PFAS [220]. The estimated cost involving an evaporated pond system was $577.9 million, with a unit cost of ranging from $1.72 to $2.71 m$^{-3}$. In comparison, a nonevaporated pond system would cost $391.9 million at a unit cost of $1.06 and $2.09 m$^{-3}$. For a photocatalytic degradation process of PFAS in water, the cost was evaluated using indium oxides at a 254 nm light source requiring 2106 kWh/m$^3$ and was found to cost $295 m$^{-3}$ for a treatment time above 11 h [221].

The cost evaluation for the photocatalytic degradation of PFAS is scant. More studies are needed to understand the cost of water

purification via photocatalytic degradation, adsorption, and membrane technique. Although the EPA-derived work breakdown structure has been developed to determine the process cost, there may be a need to modify the structure as different factors may contribute to the direct and indirect costs due to location-specific factors or variations in process specificity. However, the EPA-derived work breakdown structure may serve as a template to work with or modify in other regions of the world for cost analysis. The disposal of the spent membrane, adsorbent, and catalyst requires further study. Therefore, there is a need to develop an efficient and cost-effective system for disposing of or handling them when they are completely spent. This is an interesting area of research, finding applications for them instead of environmental disposal or incineration.

## 7. Conclusion

Contamination of drinking water by PFAS is a serious problem in developing countries that requires attention. PFAS has been reported in surface water and groundwater systems with the help of different analysis methods. With the several known PFAS, no single analysis method can comprehensively detect all the known PFAS in a single process. The legislation of national standards for PFAS is still ongoing. However, few developed and developing countries have established guidelines for handling PFAS in water. Many of the known treatment processes for PFAS in water combine separation and destruction techniques for complete removal. Unfortunately, complete defluorination is still a challenge. Despite the EPA-derived work breakdown structure, the cost implication of any technique for removing PFAS from water is not a one-sided system but requires the consideration of different factors that may be region-specific, process-specific, or situation-based. With the discontinuation of long-chain PFAS, there is a need to focus on understanding the fate and detailed health implications of the short-chain moieties in developing countries.

## CRediT authorship contribution statement

A.A.: investigation, writing, conceptualization; Q.L.: supervision, writing, conceptualization, proof reading.

## Declaration of competing interests

The authors have declared no conflicts of interest.

## Acknowledgment

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