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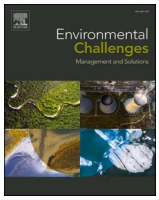

A comprehensive review on the distribution of per- and poly-fluoroalkyl substances in the environment across Sub-Saharan Africa revealed significant variation in their concentrations

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic chemicals known for their widespread use in various industrial and consumer products. They enter the food chain via contaminated water, air, and soil, resulting in bioaccumulation in plants, fishes, foods, human milk, and blood serum. Here, we critically reviewed the literature published from 2005 to 2021 on the occurrence and distribution of Perfluorooctanoic acid (PFOA) and perfluoro-octane sulfonate (PFOS) as the most occurring PFAS in the aquatic environment in sub-Saharan Africa (SSA). To our knowledge, this is the first paper to review the status of PFAS in the SSA environment. This review found that almost all matrices studied in SSA regions have been polluted by PFAS with varying concentrations. This information suggests that the levels of PFAS in the environment deserve immediate attention. Furthermore, SSA faces unique challenges in understanding and managing PFAS contamination due to the scarcity of data in specific regions and the need for more administrative guidelines for monitoring PFAS in water. This review provides vital baseline information on the occurrences, distribution and contributing factors for their distribution in the SSA environment for better understanding to protect the environment and public health, and to develop sustainable solutions for the PFAS growing concern.

Introduction

Per- and poly-fluoroalkyl substances (PFAS) have become a significant concern in manufacturing industries since the mid-20th century (Hepburn et al., 2019). These synthetic compounds are used in various products, including firefighting foams, non-stick cookware, cosmetics, paper goods, food packaging, and water repellants (Burki, 2021; Cousins et al., 2019; Glüge et al., 2020). PFAS, including short-chain varieties like per-fluorobutane sulfonic acid (PFBS) and perfluorooctanoic acid (PFBA), as well as long-chain chemicals like perfluorooctanoic acid (PFOA) and perfluorooctanoic Sulfonate (PFOS), are derived from industrial discharges, agricultural runoff, firefighting facilities, textile, leather, and electronics industries also contribute significantly to PFAS pollution in water bodies. Human exposure to PFAS is significant due to their widespread distribution in the environment, entering the food chain through contaminated water, air, and soil, leading to their accumulation in living organisms (Bolan et al., 2021; Garg et al., 2020; Liu et al., 2022). Exposure to PFAS also occurs through contact with products containing these materials, particularly for individuals working with PFAS-containing materials (Christensen and Calkins, 2023; Tansel, 2022). The environmental presence of PFAS raises ecological concerns, causing developmental defects, reduced reproductive success and abnormalities in aquatic organisms (Gong et al., 2022; Savoca and Pace, 2021). In humans, PFAS exposure is associated with health effects such as liver damage, hormone disruption, infertility, decrease in sperm count, liver diseases, and increased risk of certain cancers (Blake and Fenton, 2020; Fenton et al., 2021). Furthermore, PFOA and PFOS were phased out between 2000 and 2002 in the United States due to their detrimental effects on living organisms (Apelberg et al., 2007; Eriksen et al., 2013; Espartero et al., 2022; Vieira et al., 2013).

Despite the phase-out of PFOA and PFOS production, challenges persist regarding their environmental persistence, past uses, prevalence,

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and health effects on living organisms (Bearden et al., 2019). These chemicals resist easy breakdown in the environment, leading to long-term contamination of groundwater and surface water (Kurwadkar et al., 2022). Shorter-chain PFAS derivatives like perfluorooctanoic acid and perfluorobutanesulfonic acid, which are less bio-accumulative than their long-chained counterparts, have replaced PFOA and PFOS to address their persistence and effects (Li et al., 2020; Longpré et al., 2020). However, recent studies show an increase in the levels of currently used short-chain PFAS from 1996 to 2019, while PFOS and PFOA levels decreased (Zheng et al., 2021). Furthermore, new substitutes, such as GenX, a short-chain PFAS, have been considered hazardous even at significantly lower exposure levels than the well-known PFAS. Despite North America and Europe being the primary focus of PFAS contamination studies and public awareness, PFAS contamination is a global issue affecting many parts of the world. In Africa, there is a need for more information and awareness about the occurrence, distribution, and effects of PFAS, particularly in SSA. Some SSA countries have identified PFAS in wastewater, human serum, air, fish, soil, and water sources. Industrial activities, poor solid waste management, and the widespread use of PFAS-containing items are suspected to be the main sources of PFAS contamination in the region.

This review aims to provide an overview of the status of PFAS, specifically focusing on PFOA and PFOS as the most dominant classes of PFAS compounds in the environment. The focus extends to PFAS occurrence and distribution in central, east, south, and western African countries. The review explores the persistent nature, half-life, potential removal techniques, and factors influencing the transportation of PFAS in abiotic components. Additionally, the study elaborates on the challenges associated with overcoming and navigating regulatory guidelines for emerging micropollutants, including PFAS, in SSA.

Review methodology

We conducted a thorough analysis to assess the presence, distribution, transportation mechanisms, and various removal methods of PFAS in water and wastewater. The investigation covered countries within the SSA, categorized into southern, central, east, and western African zones. The study focused on PFOA and PFOS due to their historical usage, prevalence, and the availability of health research data. To comprehend the current state of PFAS research in SSA, a thorough literature review was carried out, involving the identification of keywords and targeted searches within specific countries.

To identify relevant PFAS contamination studies, a comprehensive search was conducted using search terms such as PFOA, PFOS, PFAS, occurrence, distribution, persistence of organic pollutants, emerging micropollutants, surface water, rivers, perfluoroalkyl, and polyfluoroalkyl substances. Various sources were used, including reports, journal articles, books, theses, and dissertations. ScienceDirect, Google Scholar®, PubMed, and Research Gate were the primary search engines used for this research.

Initially, a total of 400 studies were identified from diverse sources. To narrow down the selection, a screening process was conducted, which involved evaluating abstracts and reading the full documents. Ultimately, 40 studies were found relevant for this review. Among them, eastern, southern, and western regions each accounted for 13 studies, while one study focused on countries within the central African zone. From these studies, 29 key findings were identified and incorporated for detailed reference.

General occurrences and distribution of PFAS in SSA

PFAS, among other chemicals, hold significant importance in commercial and industrial applications globally. Their presence has been predominantly detected in the environments of developing countries, including groundwater, surface water, food, air, and human serum (Kurwadkar et al., 2022; Mudumbi, 2019; Ssebugere et al., 2020). It is worth noting that the available studies on PFAS pollution and its extent primarily focus on individual countries rather than providing a comprehensive regional or global perspective. However, different investigations on PFAS from various SSA countries, including Zimbabwe, Tanzania, Burkina Faso, Kenya, Ivory Coast, Ghana, and others (Fig 1), have reported the presence of PFAS such as PFOA, PFOS, PFBS, and perfluorohexanesulfonic acid (PFHxS) in different concentrations ranging from below the Limit of Detection (LOD) to 390 ng/L (Hope, 2020; Kaboré et al., 2018). Despite the relatively low concentrations reported in these studies, the health impacts on aquatic organisms and human beings are significant (Hope, 2020). Moreover, the lack of sufficient infrastructure and resources for extensive PFAS environmental analysis and monitoring in sub-Saharan countries (Ssebugere et al., 2020), limits the availability of comprehensive information and justifications.

Occurrence of PFAS in the East African zones (EAz)

East African countries are among the regions with clean and safe drinking water scarcity. High population growth, poor waste management and increased industrialization in most East African countries lead to high emission of pollutants such as microplastics, feedstock wastes and antibiotics (Fayiga et al., 2018; Singh et al., 2022). As a result, the quality of water in the region is deteriorating.

Studies have shown the presence of PFAS in East African countries. These harmful chemicals have been detected in various water sources, including rivers, lakes, wastewater treatment plants, sediments, fish, and even the air. The study done by Hope (2020) in the coastal areas of Tanzania and Mozambique revealed that PFOS and PFOA, two types of PFAS, were present in all analyzed water samples. The concentrations were relatively low, with the highest levels found in Tanzania and Mozambique being 0.047 ng/L and 0.053 ng/L for PFOS, and 0.0378 ng/L and 0.063 ng/L for PFOA, respectively. These concentrations are lower than those detected in Uganda's surface water 2.5 ng/L (Dalahmeh et al., 2018). However, compared with the industrialized countries, the East African zone has lower levels of PFAS, 20.5 ng/L, and 1590 ng/L of PFOA and PFOS reported in the Huangpu River in China countries (Chen et al., 2009). These higher concentrations might have been attributed to the presence of many manufacturing industries (Li et al., 2014). Similarly, a study by Hope (2020) found that Lake Victoria had been polluted by PFAS in which 0.091 ng/L – 1.5 ng/L was detected in Uganda's zone, which is comparable to those detected in Lake Superior in South America but lower than those detected in surface water in China (De Silva et al., 2011; Jin et al., 2009). Pollution in Lake Victoria was suspected to be attributed to the destruction of the wetland ecosystem that filters wastes from the city before entering the lake (Bwathondi et al., 2001). Such destruction has been caused by the proliferation of industries and the expansion of settlements. Therefore, the detected levels in the Eastern zone do not exceed the health-recommended level of 70 ng/L and 100 ng/L for PFOS and PFOA in drinking water set by the US EPA in 2016 and WHO respectively (Hu et al., 2016; WHO, 2022). On the contrary, the revised guideline of US EPA in 2022 recommends that the acceptable levels of PFOA and PFOS are 0.004 and 0.02 ng/L, respectively. In this regard, the revised guideline of 2022 places the previously reported levels above the recommended health limit (Decaminada, 2022).

Several studies report the presence of PFAS in aquatic organisms. The levels of PFAS in these organisms vary greatly depending on the type of species, the habitat in which they live, and the local environmental conditions (Bangma et al., 2022; Kavusi et al., 2022). Researchers have revealed that the fish are more likely to have greater concentrations of these chemicals in places close to industrial sites, wastewater treatment facilities, sediments, and areas with a history of PFAS usage (Ahmadireskety et al., 2021; Jarvis et al., 2021; Ojemaye and Petrik, 2019). Parts of the fish are bio-accumulated differently depending on the type of PFAS, as PFOS accumulates in the liver more than muscles, while the

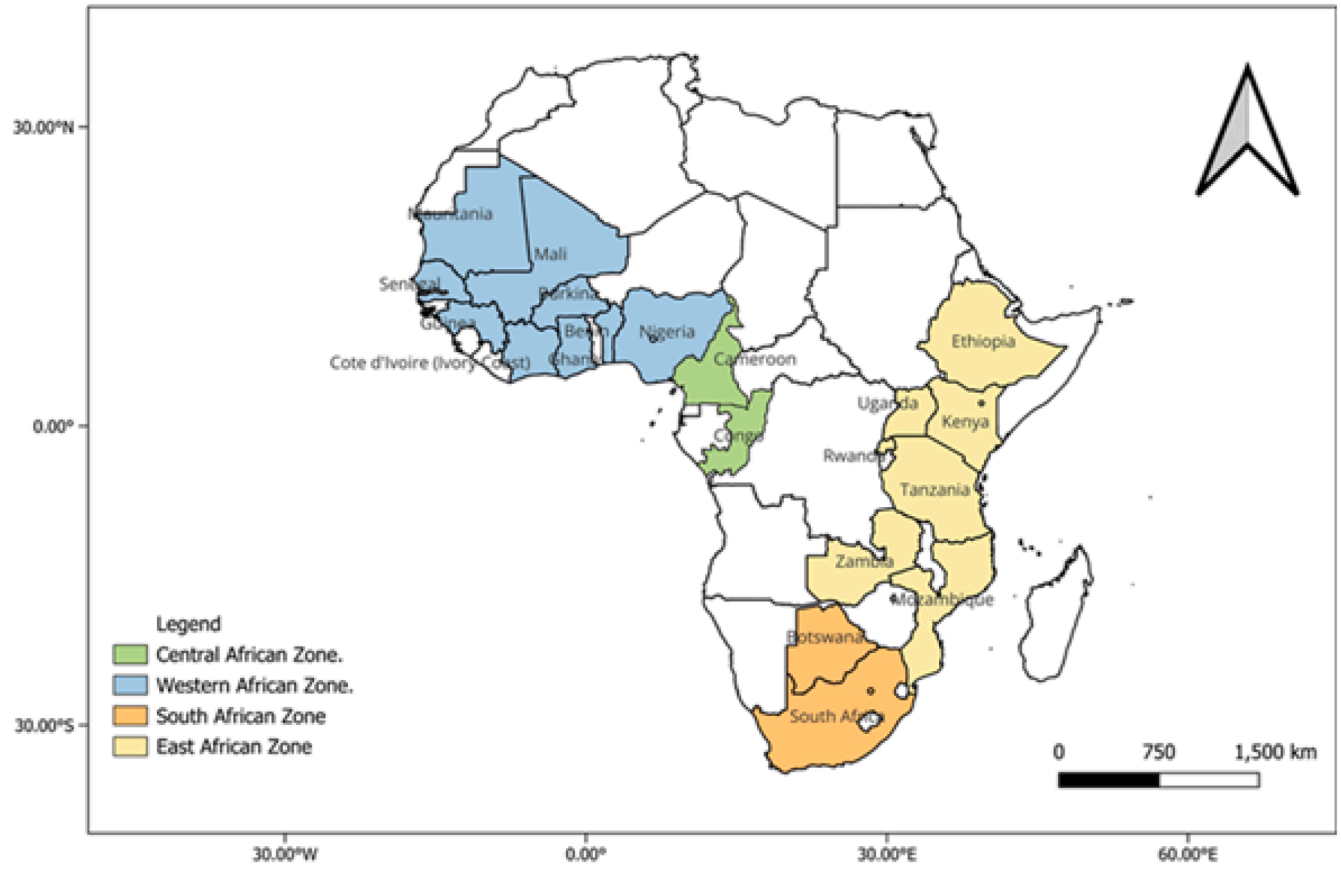

Fig. 1. Map of Africa showing countries of sub-Saharan in which PFAS were reported (Drawn by Hildegard R. Kasambala).

vice versa is true for PFOA (Stults et al., 2023). Arinaitwe et al. (2020) studied spatial profiles of perfluoroalkyl substances in Nile Perch and Nile Tilapia. The study found that the level of total PFAS was substantially higher in Nile Perch muscles near open lake 0.44 ng/g ww than in Nile Tilapia nearshore 0.24 ng/g ww. The detected level in Nile Perch and Nile Tilapia is high enough to cause effects on living organisms (Arinaitwe et al., 2020). The study conducted at Reunion Island in the Southwest of the Indian Ocean reported the highest level of 0.267 ng/g ww PFAS in shark's bull. This level was approximately twice as elevated as those obtained in tiger sharks (0.144 ng/g ww). The reason for the elevation of PFASs in the two aquatic organisms was that the bull shark mostly spends more time in shoreline habitat for feeding, where the concentration of PFAS is still high (Rediske, 2022). Mwakalapa et al. (2018) studied wild and marine fish at Mtwara, Pemba and Unguja in Tanzania. They found that all PFAS were below the detection limit, possibly due to the higher detection limit of the equipment used (0.08 to 0.43 ng/g ww). Furthermore, Groffen et al. (2021) studied the distribution of organic pollutants, including PFAS, in the aquatic environment of Tanzania. The study revealed that PFOA and PFOS are high in fish muscles found at the Ngerengere River and Mindu Dam, which are attributed to anthropogenic activities along the river and dam. The study of Orata et al. (2009) from Kenya found that the levels of PFOS in *Oreochromis niloticus* and *Lates niloticus* fished from Lake Victoria in Kenya's zone were higher than in Tanzania. The maximum values of PFOS in the muscle and liver tissues of *L. niloticus* were reported to be 10.5 and 35.7 ng/g ww, respectively, while in *O. niloticus*, PFOS were 12.4 and 23.7 ng/g ww in the same tissues (Orata et al., 2009). Also, Ahrens et al. (2016) and Arinaitwe et al. (2020) reported (5.8 and 1.75 ng/g ww) concentrations of PFOA and PFOS fish muscles found in Lake Tana, Ethiopia. The concentration of PFOS detected was not significant enough to harm the living organisms within a short exposure period. However, Bearden et al. (2019) recommend that such levels might cause health effects in prolonged exposure (Bearden et al., 2019).

Industries which use PFOA and PFOS chemicals in their processes may discharge byproducts containing such compounds into air and wastewater. The discharged pollutants may lead to elevated concentrations in water bodies such as rivers, ponds, wells, lakes, and oceans. The PFAS concentrations in wastewater differ significantly depending on the source of contamination, the nature of industrial activities in the area, and guiding local regulations (De Silva et al., 2021; Hepburn et al., 2019). The study conducted at the Lake Victoria catchment in Kenya found that the maximum levels of PFOA and PFOS in municipal waste treatment ponds were 96.4 ng/L and 11.7 ng/L, respectively. Such concentration is lower compared with those reported in South Africa (626 ng/L) and France (638 ng/L) (Chynel et al., 2021; Dewan et al., 2013; Munoz et al., 2017; Orata et al., 2009). Dalahmeh et al. (2018) conducted a study in Kampala, Uganda, on water, soil and plants cultivated in wetlands and agricultural areas. They found that Wastewater Treatment Plants (WWTPs) contribute significantly to PFAS pollution since 5.6 – 9.1 ng/L is detected in the effluent and released to the receiving environment, where it is used for various activities. The soil used for cultivation of sugar cane, maize, and yam irrigated by WWT was shown to be polluted in which total PFAS ranged from 1.6 to 4.9 ng/g, 3.0–7.9 ng/g and 4.2–5.3 ng/g, respectively. The dominant FPAS detected in wastewater was PFBS (2.3 – 3.1 ng/L), followed by PFOA (0.4–1.9) ng/L, where PFOS had levels lesser than the detection limit, while in soil, PFOS was dominant (0.6 – 3 ng/g) over all other PFAS classes (Dalahmeh et al., 2018). The concentration of PFAS in wastewater reported in Uganda was lower compared with 0.9–18.8 ng/L and 1.3–28 ng/L of PFOS and PFOA spotted by Chirikona et al. (2015) in WWTPs at the Lake Victoria catchment area in Kenya. The higher levels in Kenya are suspected to be contributed significantly by the pollutants discharged from the nearby hospital to the municipal wastewater system (Chirikona et al., 2015).

The presence of PFAS in the air is a growing environmental concern because of their effects on ecosystems and public health. The study by González et al. (2021) on air monitoring of perfluoroalkane substances conducted from 2017 to 2019 in developing countries shows that Zambia, as an African representative, was highly polluted by PFAS with the concentration of PFOS 36 ng/PUF compared to other developing countries. The higher reported level was probably attributed to the Zambia metrological station at Kenneth Kaunda International Airport, which was undergoing construction when the samples were taken (González et al., 2021). Besides, PFAS in the air can also be caused by long-range transportation from other source regions, deposition occurring through dry and wet processes, and valorization from contaminated surfaces to the air (Yao et al., 2016). Thus, ongoing research, monitoring, and international collaborations are essential to address the issues posed by persistent PFAS in the air and strive towards a more sustainable and healthier environment.

In the eastern zone, Kenya, as a highly industrialized country and regional transportation hub, has been reported to have relatively higher concentrations of PFAS. Poor waste management, overpopulation near ocean basins, urbanization, and industrial emissions contribute to PFAS pollution in cities and coastal areas (Kunacheva et al., 2012; Miglioranza et al., 2022; Pistocchi and Loos, 2009; Ssebugere et al., 2020). Most studies have reported PFAS pollution in this zone in wastewater, rivers, soil, aquatic organisms, and air. However, the evidence of their presence in groundwater is limited. The studies' findings indicate that Lake Victoria's shore waters, bordered by all the countries, are polluted by PFAS (Table 1). While current levels may not exceed recommended health limits, ongoing monitoring, proper waste management, and international collaborations are vital to mitigate the possible long-term impacts on the environment and public health.

Occurrence of PFAS in the Southern African zone (SAz)

PFAS contamination has been observed in various environmental media throughout Southern Africa, including water bodies, soil, sediments, wildlife, and human populations (Groffen et al., 2018). The sources of PFAS contamination in this region can be attributed to industrial discharges, firefighting foams, landfills, wastewater treatment facilities, and agricultural runoff. These activities contribute to the wide distribution of PFAS pollutants. PFAS are characterized by their high persistence in the environment, resulting in long-term contamination of surface water bodies. The high solubility of certain PFAS compounds make them readily dissolve in surface water, groundwater, and oceans. Consequently, these environmental compartments serve as the primary sink for PFAS pollutants (Kurwadkar et al., 2022). The persistent nature and widespread distribution of PFAS emphasize the need for comprehensive monitoring and remediation efforts to mitigate their environmental and human health impacts.

A study conducted by Mudumbi (2012) in the Western Cape rivers of South Africa revealed significant levels of PFOA and PFOS in river water samples and suspended solids. The highest concentrations were observed in Diep River, with levels of 314 ng/L for PFOA and 182 ng/L for PFOS. These elevated concentrations can be attributed to wastewater effluents from nearby industrial areas and sewage systems. The presence of higher levels of PFAS pollution in the province may also be linked to agricultural practices and industrial activities in the vicinity (Saucy et al., 2018). The concentrations of PFOA and PFOS reported in these rivers are higher than those found in other studies worldwide (Ssebugere et al., 2020). In developing countries, river water is commonly used as a source of drinking water, and the observed levels of PFOA and PFOS in these rivers exceed the recommended limits proposed by relevant authorities. For example, the U.S. SEPA proposed a threshold of 70 ppt for PFOA and PFOS in 2016, while the European Food Safety Authority proposed two ppt for PFOA, PFOS, PFNA, and PFHxS in 2020. Additionally, in 2022, the U.S. EPA proposed limits of 0.004 ppt and 0.02 ppt for PFOA and PFOS, respectively, as well as ten ppt and 2000 ppt for GenX and PFBs (Thagard, 2022). Such elevated levels of PFAS pollution in the region pose potential health risks to humans and the entire ecosystem. It is crucial to address and mitigate these contamination levels to safeguard public health and protect the environment.

Table 1
The concentration and types of PFAS found in EAz media.

PFAS reported	Polluted countries in EAz	Type of media	Concentration (ng/L[a], ng/g ww[b], ng/g[c], ng/PUF[d])	Reference
PFOS	Tanzania	Lake	LOD-0.047[a]	(Hope, 2020; Müller et al., 2019)
PFOA			LOD-0.053[a]	
PFNA, PFDA, PFUdA, PFHxS and PFOS		Human tissue	0.14–0.5[b]	
PFOS	Mozambique	Lake water	LOD - 0.037[a]	
PFOA			LOD - 0.063[a]	
PFOS	Kenya	Surface water	0.0009–0.018[a]	(Chirikona et al., 2015)
PFOA			1.3–28[a]	
PFOS		WWT	0.9–18[a]	
PFOA			1.3–28[a]	
PFOS	Kenya	Fish tissue	LOD-35.7[b]	(Orata et al., 2009)
PFOS		Fish tissue	LOD-23.7[b]	
PFOA		WWT	96.4[a]	
PFOS			11.7[a]	
∑PFAS	Ethiopia	Fish tissue	LOD-5.8[b]	(Ahrens et al., 2016)
		Surface water	0.073–5.6[a]	
		Sediments	0.22–0.55[a]	
∑PFAS		Fish tissue	0.44 and 1.75[b]	(Arinaitwe et al., 2020)
PFBS, PFOA, PFOS	Uganda	WWT	0.4–3[a]	(Dalahmeh et al., 2018)
		Soil	0.0–3.0[c]	
PFHxS, PFOS, PFDS, PFHxA		Soil	LOD-0.00149[c]	(Rankin et al., 2016)
∑PFAS		WWT & soil	5.6–9.1[ac]	
PFOS, PFOA, FOSA, PFHxS	Zambia	Air	LOD-36.0[d]	(González et al., 2021)

Concentration unit for:
[a] Aqueous media.
[b] Tissue media.
[c] Soil media.
[d] Air media. WWT = Wastewater; LOD = Limit of detection.

Several studies have been conducted to investigate the occurrence of PFAS in fish species in SAz (Goodrow et al., 2020; Miranda et al., 2023; Simukoko et al., 2023; Suominen et al., 2011). Abafe et al. (2021) reported the presence of PFAS in marine shellfish in South Africa. They detected Perfluorooctanoic Acid (PFPeA) with a concentration range of 4.83–6.43 ng/g ww in fish muscles, along with a relatively higher concentration of PFOS in fish muscles (289 ng/g ww) and in the liver (34 ng/g) in the Vaal River, South Africa. The high levels of PFAS detected in fish may be associated with industrial pollution near the river. In another study by Ojemaye and Petrik (2019) conducted at Kalk Bay Harbour in Cape Town, they reported the presence of perfluorodecanoic acid (PFDA) ranging from 20.13 to 179 ng/g, followed by perfluoroheptanoic acid (PFHpA) ranging from 40.06 to 138.30 ng/g in pelagic fish species. These findings indicate that the bioaccumulation of PFAS increases with the carbon chain length (Sun et al., 2022).

Consuming fish with high levels of PFAS can potentially expose humans to various health risks, including developmental and reproductive effects, obesity, and cancers (Anderko and Pennea, 2020; Beale et al., 2022; Blake and Fenton, 2020; Enyoh et al., 2023; Liew et al., 2018; Panikkar et al., 2019; Quinete and Hauser-Davis, 2021). Therefore, it is important to monitor and regulate the presence of PFAS in fish and other seafood to minimize human exposure and protect public health.

Studies have also investigated the occurrence of PFAS contaminants in various sources, including cord blood, dairy milk, and infant formula. A study conducted in South Africa by Hanssen et al. (2010) reported the presence of PFAS contaminants in the maternal serum and cord blood of women. The study revealed that PFOS was the dominant contaminant in maternal serum, with a concentration of 1.6 ng/mL, followed by PFOA (1.3 ng/mL and PFHxS (0.5 ng/mL). However, Table 2 revealed that PFOA was the most prevalent in cord blood, followed by PFOS and PFHxS. Urban and semi-urban women showed significantly higher levels of PFAS contaminants, potentially due to their higher standard of living.

A study conducted in South Africa by Macheka et al. (2021) focused on the contamination of PFAS in retail dairy milk and infant formula indicated the presence of at least four types of PFAS in each sample, with a particularly high frequency of PFuDA. The study associated the higher frequency of PFuDA with the disintegration of volatile products like telomer alcohols (Jahnke et al., 2007). It is important to note that the levels of PFAS contamination observed in these South African samples were not significantly different from those detected in Poland (Sznajder-Katarzyńska et al., 2019).

While numerous studies have been conducted on water and aquatic organisms (Table 2), research on PFAS pollution in the air remains limited. Therefore, further studies are needed to provide substantial evidence of PFAS contamination in the atmosphere.

Table 2
The concentration and types of PFAS in the Southern African zone (SAz).

PFAS reported	Polluted countries in SAz	Media	Concentration (ng/L[a], ng/g[b], ng/PAS[c])	References
PFOS, PFOA, PFHxA	South Africa	Human tissue	1600, 1300, 500[b]	(Hanssen et al., 2010)
		Human tissue	700, 1300, 300[b]	
PFBA, PFPeA, PFBS, PFHxA, PFHpA, PFxS, PFOA, PFNA, PFOS, PFDA, PFUdA, PFDS, PFDoA		Infant formula	LOD–2760[b]	(Macheka et al., 2021)
PFPeA, PFOS, PFHxA and PFTeDA		Fish tissue	4.83–6.43[b]	(Abafe et al., 2021)
PFOS		Fish tissue	34.00–289.00[b]	(Groffen et al., 2018)
PFDA	South Africa	Fish tissue	20.13–179.00[b]	(Ojemaye and Petrik, 2019)
PFUnDA & PFDA		Fish tissue	78.86–124.40[b]	
PFNA, PFHpA& PFOA			37.52–83.86[b]	
PFOA		River water	390.00[a]	(Mudumbi, 2019)
PFOS			47.00[a]	
PFOA		River water	314.00[a]	
PFOS			182.00[a]	
PFOA		River water	146.00[a]	
PFOS			23.00[a]	
PFOS, PFOA, PFNA PFDA, PFUdA, PFDoA	Mauritius	Egg chicken	0.14–3.8[b]	(Van der Schyff et al., 2020)
MEFOSA, EtFOSA, MeFOSE, 8:2 FTOH, 10:FTOH	Botswana	Air samples	LOD-11.00[c]	(Gawor et al., 2014)

Concentration unit for
[a] Aqueous media.
[b] Tissue media.
[c] air media. LOD = Limit of detection.

Occurrence of PFAS in the West African zone (WAz)

The safety and quality of drinking water pose significant concerns, especially in developing countries. The presence of emerging micropollutants, including PFAS, released into aquatic environments directly impacts the quality of drinking water (Lapworth et al., 2012; Pal et al., 2014; Papagiannaki et al., 2022; Sui et al., 2015; Tang et al., 2019). Kaboré et al. (2018) conducted a comprehensive global study on bottled drinking water, revealing maximum detected concentrations of PFBA, PFBS, PFOA, and PFHxS at levels of 1.3 ng/L, 1.6 ng/L, 3.0 ng/L, and 0.67 ng/L, respectively. Particularly, PFOA levels in Ivory Coast were considerably higher at 3 ng/L compared to Canada, resembling concentrations found in Chinese tap water (3.9 ng/L), but lower than those observed in Florida drinking water PFOS (20–70 ng/L). In Burkina Faso, the dominant contamination of 5:3 Fluorotelomer carboxylic acid (5:3 FTCA) at 3.9 ng/L was attributed to potential infiltration from municipal landfills, which could potentially contaminate surface water reservoirs (Hu et al., 2016; Mak et al., 2009).

Long-chain PFAS, such as PFOA and PFOS, are known to accumulate in the serum of human beings when consumed through drinking water. This accumulation has been observed in numerous developed countries (Bartell et al., 2010; De Silva et al., 2021; Glenn et al., 2021; Teymourian et al., 2021). In a study conducted by Essumang et al. (2017) in Ghana, PFAS levels in rivers and tap water were assessed. The predominant pollutants detected were PFDA, PFHxA, PFOS, and PFPeA. The sum of PFAS reached 398 ng/L in River Pra, 281 ng/L in Kakum River, and 200 ng/L in tap water. High concentrations of PFOA were detected in rivers (ranging from 1.78 ng/L to 321 ng/L) and tap water (ranging from 66 ng/L to 190 ng/L), potentially due to inefficiencies in nearby treatment plants (Essumang et al., 2017). These findings highlight the need to address treatment plant issues in WAz and implement measures to mitigate PFAS contamination in water sources to ensure the safety of drinking water.

A global monitoring plan (GMP) was set up by the Stockholm Convention on Persistent Organic Pollutants (POPs) to check for PFOA, PFOS, and PFHxS in surface water in several countries, such as Ghana and Senegal (Baabish et al., 2021; Jin et al., 2009; Senthilkumar et al., 2007). The variability in PFAS levels observed in these different regions can be attributed to various factors, such as point sources of contamination, seasonal variations in sampling, and historical activities like firefighting, wastewater treatment plants (WWTPs), industrial activities, and agricultural (Baabish et al., 2021; Podder et al., 2021). These factors contribute to the differing levels of PFAS contamination observed in surface water across the monitored areas.

The Monitoring Network (MONET) conducted a monitoring pilot study in various African countries, including Nigeria, between 2013 and 2014 to assess PFAS water surface pollution. The study revealed that Nigeria had the highest level of PFOS, with a concentration of 1.39 ng/L, while the other countries exhibited lower levels (Kurwadkar et al., 2022). The relatively higher reported level of PFAS in Nigeria is likely due to the presence of numerous industries, including manufacturing and oil and gas extraction. Sindiku et al. (2013) conducted a study in Nigeria, detecting seven major perfluoroalkyl carboxylates (PFCAs) and three perfluoroalkyl sulfonates (PFSAs) in WWT sludge. The study highlighted that PFOS was the dominant contaminant, ranging from 1.01 ng/g to 5.40 ng/g, while PFOA ranged from 19 ng/g to 416 ng/g. These levels were lower compared to those detected in Shanghai, China (Sindiku et al., 2013; Zhang et al., 2015). The high levels of PFOA and

PFOS in wastewater sludge correspond to the high concentrations of PFAS in wastewater influents and effluents. However, in this region, there is a limited amount of research on PFAS pollution in WWT. We need to conduct further studies to enhance our understanding of PFAS contamination in wastewater treatment systems.

When examining the presence of PFAS in roasted fish in Mali, Nigeria, Cameroon, and Benin, significant concentrations of PFOS (LOD - 0.01044 ng/g) were found in Bamako and Sikasso in Mali. The extensive use of pesticides in agricultural practices could potentially be the cause of this (Tomy et al., 2004; Vaccher et al., 2020). The simultaneous detection of pesticides and PFOS in smoked fish samples further supported the correlation between pesticide usage and PFOS (Amaraneni and Pillala, 2001; Liu et al., 2017). Mali detected higher levels of PFAS than Tanzania, but found lower levels compared to Uganda, Ethiopia, Kenya, and South Africa (Arinaitwe et al., 2020; Groffen et al., 2021; Mwakalapa et al., 2018).

Additionally, PFAS have been discovered in human blood serum, with their levels measured in ppb, ng/mL, or μg/L (Gaballah et al., 2020). The common PFASs found in African human samples are PFOS and PFOA (Ssebugere et al., 2020). Timmermann et al. (2020) conducted a study in Guinea-Bissau, reporting the highest level of 0.77 ng/mL of PFOS and the lowest level of 0.1 ng/mL of PFHxS in human blood samples. These detected levels were associated with a decrease in pre-vaccination measles antibody levels among vaccinated children. The levels of PFAS in human blood serum can vary depending on several factors, including direct exposure to PFAS-contaminated areas or facilities (Lloyd-Smith and Senjen, 2015) Studies investigating PFAS pollution at multiple military sites in Australia, where the use of Aqueous Film-Forming Foam (AFFF) in firefighting drills resulted in high concentrations of PFAS in people's serum, have supported this (Lloyd-Smith and Senjen, 2015). Furthermore, studies in sub-Saharan Africa have detected various types of PFAS in the western zone (Table 3).

Occurrence of PFAS in the Central African zone (CAz)

Based on the evidence from several studies which report that PFAS is a global concern, the Central African zone cannot be excluded. Currently, there is limited information regarding PFAS pollution in this zone. However, the study by Bayebila et al. (2021) at Congo Kinshasa on emerging contaminants, including PFAS, in human samples. The author noticed that very few individuals were contaminated with PFAS. The observed minor contamination may be attributed to the relatively small sample size ($n = 15$) employed in the study.

Additionally, a monitory pilot study (MONitoring NETwork - MONET) conducted in Africa between 2013 and 2014, focusing on PFAS water surface pollution, revealed that Congo demonstrated the lowest concentration, approximately 0.035 ng/L, compared to other countries such as Egypt, Kenya, Mauritius, Morocco, and Nigeria (Kurwadkar et al., 2022). Particularly, Democratic Republic of Congo is the only country within this zone where studies on PFAS pollution have been conducted. The scarcity of information give emphasis to the need for further research studies and increased awareness initiatives to establish the actual extent of PFAS pollution in countries within the Central African zone.

Summary of PFAS occurrence in SSA

In general, PFAS contamination has been identified across all regions of the SSA. The detected PFAS levels vary from one zone to another and within the zones in between the countries. Among the SSA countries analyzed, only 20 nations have conducted PFAS studies accompanied by statistical data. Moreover, a significant proportion of PFAS studies is concentrated in the western zone (ten studies in eight countries), southern zone (nine studies in four countries), eastern zone (eight studies in six countries), and central zone (two studies in two countries) (Fig 2). The distribution of studies corresponds to percentages of 34 %, 31 %, 28 %, and 6.9 % in the western, southern, eastern, and central zones, respectively. South Africa, Nigeria, and Kenya emerge as countries with a higher frequency of studies compared to others within their respective zones. The elevated number of PFAS studies in South Africa, Nigeria and Kenya may be attributed to these countries' proficiency in analytical chemistry and instrumentation (Ssebugere et al., 2020)

Nevertheless, the limited number of studies in certain countries

Table 3
Level of PFAS in various media in the different countries of WAz.

PFAS reported	Countries polluted by PFAS in WAz	Types of media	Concentration (ng/L[a], ng/g[b], ng/PUF[c], mg/L[d])	References
PFOS	Nigeria	Surface water	1.390[a]	(Kurwadkar et al., 2022)
PFBS		WWT sludge	0.138[a]	(Sindiku et al., 2013)
PFOS			0.101–0.540[a]	
PFOA			0.119–0.416[a]	
PFHxS			0.042[a]	
PFOS, PFINA		Beef samples	0.03–0.1[b]	(Vaccher et al., 2020)
PFBS, PFOS, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA	Nigeria	Dumpsites soil	0.05–5.0[b]	(Ibor et al., 2020)
		Fatty food	<LOD	
PFNA, PFDA, PFUnA & PDDoA	Mali	Smoked fish	LOD-0.0001440[b]	(Vaccher et al., 2020)
	Benin,	Fatty food	0.09–0.54[b]	
		Eggs, nuts, meat	<LOD	
	Cameroon	Roasted fish	0.03–0.89[b]	
PFOA, PFOS, PFHxS	Senegal	Surface water	0.03–0.55[a]	(Baabish et al., 2021)
FBSA, FHxSA, PFPrS, PFPeS, PFHpS & PFOA	Ivory Coast	Bottled drinking water	LOD–3.00[a]	(Kaboré et al., 2018)
5:3 FTCA, FBSA, FHxSA, PFPrS, PFPeS, PFHpS& PFEtS	Burkina Faso,	Bottled drinking water	LOD-3.90[a]	
PFHxA, PFOA, PFOS, PFPeA, PFDA, PFHpA	Ghana	Tap water	LOD–190[a]	(Essumang et al., 2017)
PFHxA, PFOA, PFOS, PFPeA, PFDA		River water	LOD- 321[a]	
PFOA, PFOS, PFHxS		Surface water	0.080–1.210[a]	(Baabish et al., 2021)
PFOS	Guinea-Bissau	Human serum	LOD–0.77[b]	(Timmermann et al., 2020)
PFHxS			LOD-0.1[b]	

Concentration unit for:
[a] Aqueous media.
[b] Tissue media.
[c] Soil media; and
[d] Air media. WWT = Wastewater; LOD = Limit of detection.

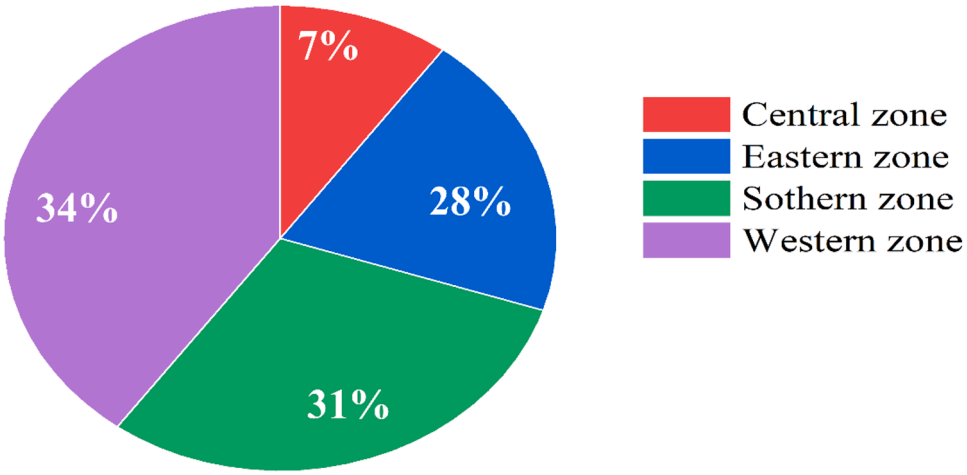

Fig. 2. Percentage of PFAS studies done in western, southern, eastern, and central zones of SSA.

hinder the availability of data on PFAS pollution, thereby impeding a true understanding of their occurrence within the SSA. Consequently, the formulation of effective policies for PFAS pollution control can only be possible when evidence from research becomes available.

Transportation and distribution of PFAS in the abiotic components

Per- and polyfluoroalkyl substances are transported in the environment through complicated processes controlled by several factors. In managing and mitigating the environmental impact, it is essential to understand the factors that affect PFAS transportation in biota generally.

The chemical properties of PFAS affect the movement of PFAS in all types of media. Chemical structure significantly influences the transport behavior of PFAS in the environment (Lyu et al., 2022). Although they have a variety of structural characteristics, they all share the chemical property of having at least one perfluorocarbon moiety (-CnF2n-) (Mifkovic, 2023). They are connected to a functional group such as carboxylic or sulphonic acid (Beale et al., 2022). The strong carbon-fluorine bond defines PFAS's persistent nature in the environment and their ability to be transported over longer distances, making them resistant to degradation (Das and Ronen, 2022; John et al., 2022; Lyu et al., 2022). This persistence ability can allow PFAS to continue to be transported through different environmental compartments over time.

The transport of PFAS in aquatic environments is significantly influenced by its solubility in water (Jeon et al., 2011; Li et al., 2022; Qi et al., 2022). Since PFAS are often highly soluble in water, both surface water and groundwater can transport them. Higher solubility compounds typically have greater mobility. Viticoski et al. (2022) study of the spatial distribution of PFAS in Alabama in United states, showed an increase in mass fluxes as rivers moved in Alabama with high concentration in Coosa River ∑PFAS 237 ng/L, the one with multiple sources. The higher concentration indicates that mass transport in aquatic environments prevails (Viticoski et al., 2022). Short-chain PFAS are more frequently detected since they are persistent and mobile in aquatic systems, providing more significant threats to human and ecological health (Li et al., 2020).

The study by Liu et al. (2019) on the contamination profile of PFAS in groundwater indicates that local hydrogeology, groundwater flow rates, direction of flow and the presence of geological barriers or channels influence the movement of PFAS in groundwater. Therefore, groundwater in this region is affected by industrial sources to some degree because PFAS can be transported over long distances in groundwater systems under the influence of the stated factors (Liu et al., 2019; Rafiei and Nejadhashemi, 2023). Also, the transportation patterns of PFAS depend significantly on the source of contamination. Localized contamination hotspots of PFAS can be caused by point sources, including industrial discharges or the locations where firefighting foam is applied, while non-point sources can cause more widespread but lower concentration pollution (Ngata et al., 2018; Robuck, 2020; Steele, 2020). Furthermore, most PFAS are hydrophilic; longer-chain PFAS are more hydrophobic as their partitioning in water and sediments media may be impacted by this hydrophobicity's effect on how they are distributed between the aqueous phase and organic matter in soils and sediments (Crone et al., 2019; Vu and Wu, 2022).

Understanding these factors is vital for evaluating the risks connected with PFAS pollutants and developing actual strategies for containment, remediation, and regulatory measures to limit their transport in abiotic components of the environment in SSA. Additionally, ongoing research is crucial to comprehend the behavior of PFAS compounds and their long-term impacts on ecosystems and human health in developing countries.

Fate, persistence, and half-life of PFAS in environment

Determination of how PFAS flow through biological systems, waterways, and soil is essential to comprehend their fate. PFAS persist in surface water bodies, leak into groundwater, and accumulate in sediment due to mobility (Ritter, 2002; Sharma et al., 2016). Furthermore, they can concentrate in human and animal tissues due to their bioaccumulation ability (Teunen et al., 2021), posing a threat to ecosystems and potentially impacting human health (Fig 3).

Degradation of most PFAS can be relatively slow in the environment, while few can break down more quickly. Thus the persistence of PFAS in water and soil can be described by its half–life as the time it takes for them to be decreased to 50 % in the respective medium (Pfeffer et al., 2023). The half-life of a PFAS compound can vary widely depending on its chemical structure and environmental conditions, such as temperature, pH and the presence of other chemicals (Liu and Avendaño, 2013). Moreover, the half-life of PFAS depends on the media in which PFAS are bioaccumulated. According to Nicole (2020) half-life of long-chained PFAS is longer than those of short-chain PFAS. For instance the study done by Lloyd-Smith and Senjen (2015) shows that the half-life of long-chain PFAS such as PFOS and PFOA in human serum can be up to 5.4 and 3.8 respectively while short-chain PFAS, such as PFPeS, in human serum are significantly low. Resistance to degradation for a long time in the biota makes PFOA and PFOS to be termed as "forever chemicals" (Peritore et al., 2023; Vakili et al., 2021). Another study by Drew et al. (2022) shows that PFAS can be bio-accumulated in cattle tissues and serum through drinking water, food, ambient air and direct contact with the product emitting by PFAS chemicals. The estimated

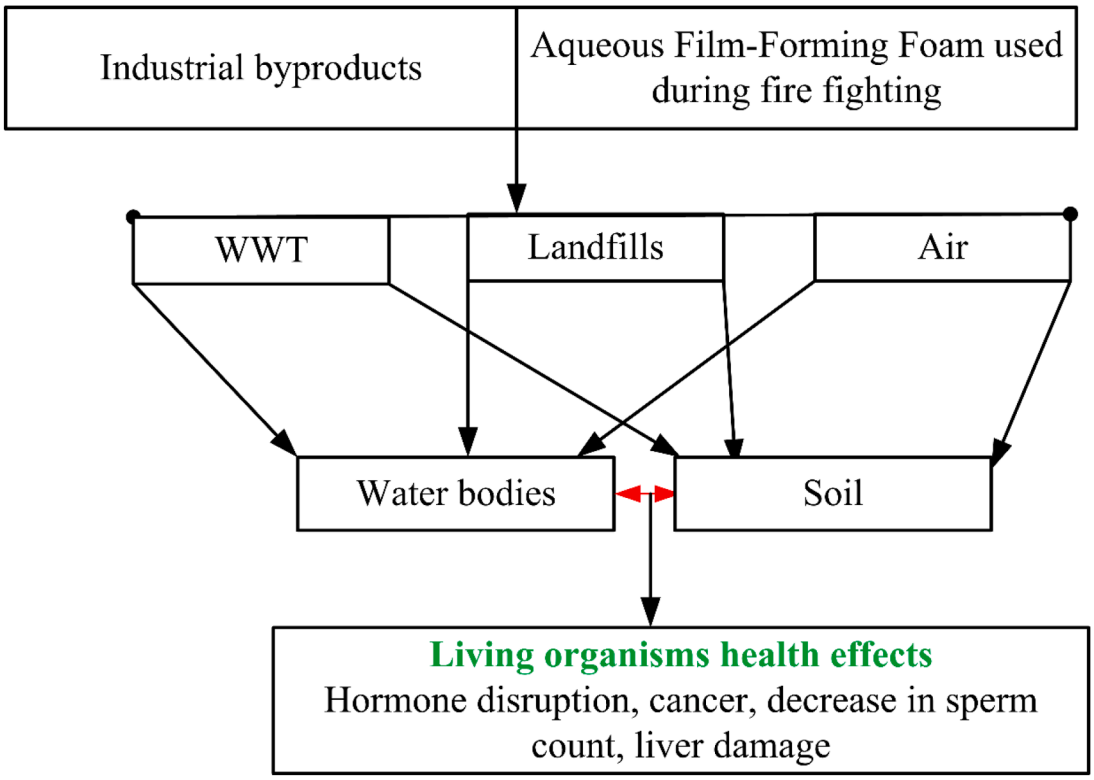

Fig. 3. The conceptual framework for the fate of PFAS in an ecosystem with red arrows in contamination and green arrows in bioaccumulations.

half-life for PFHpS, PFHxS, PFINA, PFIDA, PFOA and PFOS in serum cattle ranged from 12 days for PFINA to 6 years in PFHxS (Table 4).

The half-life for PFAS varies also according to the media from which the chemicals originated, the types of PFAS and the presence of other factors. For instance, the half-life is very high in soil and human serum compared to water, atmosphere, and cattle serum (Table 4). Long-chained PFAS may lead to health problems as they undergo bio-accumulation in protein-rich components such as blood, liver, kidney and bones (McPartland, 2019). In contrast, short-chain PFAS bio accumulate in organs and tissues like the lungs and brain (Mudumbi, 2019). The higher bioaccumulation appeared in long-chained PFAS than in short-chain PFAS due to more C-F bonds, making them more stable for them to undergo degradation. Moreover, long-chain PFAS often have lower vapor pressure and are less soluble in water; they are more likely to remain in soil, sediment, serum and groundwater rather than to diffuse through the environment (Teymourian et al., 2021). This decreased mobility makes it more difficult for natural processes to decompose them. The lengthy half-life of PFAS in the serum of live organisms and the environmental matrices is several years to decades. Because of this, PFAS persistence is a complicated problem; more research is still needed to learn more about how distinct PFAS compounds behave in different environmental contexts for easy control.

Techniques used to remove PFAS in aqueous media

In SSA, air, water, soil, and biota are contaminated with PFAS, where wastewater effluents play a significant role. Even though the environment in SSA is polluted with emerging micropollutants such as PFAS, most research focuses on analyzing water quality and removing contaminants, such as nutrients, fecal coliform, and heavy metals. However, few studies that have been done on the removal of such emerging micropollutants revealed that the techniques used for their removal are less effective (Kasambala et al., 2019; Vu and Wu, 2022). On the other hand, lack of analytical tools, such as liquid chromatography (LC-MS), expertise (Sheriff et al., 2020), and lack of emphasis by regional or global environmental or drinking water guidelines on emerging organic contaminants are anticipated causes of the limited information. In this regard, this section focuses on reviewing the types of techniques used and their strengths and weaknesses in removing PFAS from wastewater.

Biodegradation

In most developing countries, biodegradation is the principal method of removing pollutants in wastewater (Anderson et al., 2022). In certain environments, some bacteria can degrade certain PFAS and lower the levels of PFAS in effluents (Araújo et al., 2022; Ilieva et al., 2023). In some cases, the levels of PFAS in effluent can become apparently higher than those in influents. The literature revealed that such abnormalities are caused by the transformation of PFAS precursor compounds to highly persistent compounds in WWTPs (Liu et al., 2023; O'Connor et al., 2022; Schultz et al., 2006; Vo et al., 2020), Some PFAS, such as Fluorotelomer alcohols, Fluorotelomer sulfonates and perfluoroalkyl phosphate esters can be transformed into other types of PFAS, which were sometimes absent in influent or found in low concentrations, leading to apparent negative removal rates (Buck et al., 2011; Zhang et al., 2021b; Zhang et al., 2013). Study by Ilieva et al. (2023), revealed that PFAS with long-chained C6 – C12, such as PFOA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA and PFDoDa appear to have negative removal efficient with removal media efficiencies of −50 % to 0 %. Furthermore, Carp (*Cyprinus carpio*) was observed to transform the branched isomer of PFOSA into branched PFOS; maybe this is a reason for the higher level of PFOS in the ecosystems (Chen et al., 2015). Generally, WWTP can be categorized into Activated sludge (AS), oxidation ditch (OD) and lagoon. In some cases, a combination of treatment methods may be necessary in order to achieve effective PFAS pollutant removal, such as a combination of two or more biological processes (2Bio), biological and advanced treatment (Bio + Advs.) and membrane bioreactor (MBR) (Ilieva et al., 2023). Furthermore, the choice of method often depends on the specific physical properties of the wastewater and the regulatory requirements in the region. Therefore,

Table 4
The half-life of different types of PFAS in different media.

Media accumulated	Name of PFAS	Abbreviation	Half-life (years)	References
Human serum	Perfluorohexane sulfonic acid	PFHxS	2.8 −5.3	(Li et al., 2018; Lloyd-Smith and Senjen, 2015; Nicole, 2020; Olsen et al., 2005)
	Perfluorooctanoic acid	PFOA	2.7 −3.8	
	Perfluorooctane sulfonic acid	PFOS	2.9 −4.8	
	Perfluoropentane sulfonic acid	PFPeS	0.63	
	Perfluorobutane sulfonic acid	PFBS	0.07	
Cattle serum	Perfluorooctanoic acid	PFOA	2.9	(Drew et al., 2022)
	Perfluorooctane sulfonic acid	PFOS	3.7	
	Perfluorohexane sulfonic acid	PFHxS	6.0	
	Perfluorodecanoic acid	PFDA	0.165	
	Perfluorohexane sulfonic acid	PFHpS	0.123	
	Ammonium perfluoro-isononanoate	PFINA	0.034	
Atmosphere	Perfluorooctanoic acid & Perfluorooctane sulfonic acid	PFOA & PFOS	0.25–0.31	(Cooke and Emergency, 2017; WHO, 2022)
Water			92 & 41	
Soil	PFOS	PFOS	> 130	(Russell et al., 2008)
	Fluoroacrylate Polymer	AFTP	120–1700	

more studies must be conducted in the SSA to establish the regulatory requirements in the SSA to establish the effective removal of PFAS in WWT.

Activated carbon and PFAS removal

Granular activated carbon (GAC) is a popular adsorbent for removing PFAS. These chemicals adhere to the carbon surface as wastewater is transported over a bed of GAC (Ekesiöö, 2023). Generally, GAC may be helpful in the removal of long-chain PFAs such as PFOA and PFOS. However, it is thought to be less effective for removing precursors and short-chain PFAs such as PFBA and PFBS (Ekesiöö, 2023; Ross et al., 2018). Also, adsorption on GAC has less efficiency in removing low-concentration PFAS from groundwater (Zaggia et al., 2016), therefore, this is not practicable for routine uses.

Biochar and PFAS removal

Adsorption by using biochar from agro waste raises attention nowadays due to its availability in SSA, large surface area, porous structure, and strong adsorption abilities (Liu et al., 2018; López et al., 2020). Biochar has been studied as a potential method for removing PFAS from water and soil. Physical and chemical interactions cause PFAS molecules to be adsorbed to the surface of biochar. The adsorption procedure is significantly influenced by the hydrophobic properties of PFAS compounds and the hydrophobicity of the surface area of the biochar (Askeland et al., 2020; Zhang et al., 2021a). The advantage of using biochar is the ability to be regenerated after reaching its adsorption limit by heating to remove adsorbed PFAS (Foong et al., 2022; Masebinu et al., 2019). It is crucial to dispose appropriately of the used biochar to avoid recontamination. Hence, more studies must be conducted to find the best way of disposing of the usable biochar containing PFAS to avoid environmental pollution.

Anion exchange resins and PFAS removal

Del Moral et al. (2020) study shows that anion exchange resins have functional groups that can swap out PFAS ions in the wastewater for chloride or sulfate ions. The resin can be regenerated after becoming saturated with PFAS. Anion-exchange resins can remove various long- and short-chain PFAS but are challenging to remove shortest chains. More studies must be conducted to test the method for the PFAS precursors since the information still needs to be identified. Tow et al. (2021) studied managing and treating PFAS using membrane concentrates. They observed that Reverse Osmosis (RO) systems and Nanofiltration (Dulsat-Masvidal et al., 2022) can successfully reduce PFAS chemicals from the environment. However, these systems do not entirely remove PFAS but produce concentrated residues that need other attention (Tow et al., 2021). When used with other pretreatment techniques, these systems effectively remove debris and pollutants that could clog the membrane. Some facilities use advanced treatment systems such as oxidation and hybrid systems to achieve higher PFAS removal efficiencies. For Ultraviolet photolysis, UV light can break PFAS molecules into less hazardous components and even complete mineralization into carbon dioxide and other byproducts (Leung et al., 2022; Li et al., 2020). Sometimes, a chemical process using hydrogen peroxide and iron catalysts can oxidize and degrade PFAS compounds but seem to form shorter-chain PFAS when applied *in situ* (Suthersan et al., 2016). The development of potentially toxic byproducts or residuals due to the breakdown of PFAS may necessitate additional treatment or disposal. Moreover, UV light sources with relatively high energy can be expensive and energy-intensive to run continuously, especially for large-scale water treatment applications (Iervolino et al., 2020; Shannon et al., 2008), so it can be challenging to be affordable by most sub-Saharan countries.

Electrochemical oxidation and PFAS removal

Electrochemical oxidation is another technology for removing PFAS from water and wastewater. Depending on the precise electrochemical method being used for PFAS removal, this causes the formation of reactive species, such as hydroxyl radicals (•OH) or persulfate radicals (SO_4•) (Leung et al., 2022; Schaefer et al., 2017; Zango et al., 2023). These reactive species are capable of oxidizing PFAS molecules. The carbon-fluoride bonds in PFAS molecules are attacked by hydroxyl radicals or other reactive species, which fragment the molecules into more minor and less dangerous byproducts (Crimi et al., 2017; Isowamwen et al., 2023). When applied correctly, the electrochemical method can achieve high PFAS removal rates. Moreover, energy consumption, which raises running costs and toxic byproduct formation such as perchlorate and bromate, Chlorine gas and hydrogen fluoride, can hinder the application of the method (Garcia-Segura et al., 2020; Ross et al., 2018; Wanninayake, 2021).

It is important to note that the specific PFAS compounds present, their quantities and the water quality can all affect the effectiveness of the technology. In rare circumstances, combining treatment approaches may be necessary to thoroughly remove PFAS because no single technology is satisfactory for all circumstances. To avoid future environmental pollution, PFAS-contaminated materials generated during treatment should be disposed of in compliance with local regulations.

The challenges of PFAS in sub-Saharan Africa

Per- and polyfluoroalkyl substances pose significant challenges worldwide, including in Africa, where various factors increase their

impact. A major problem in Africa's fight against PFAS is the lack of thorough information and awareness (Ng et al., 2021). Insufficient studies hindered a thorough understanding of the distribution, routes of exposure, and effects of emerging micropollutants, including PFAS, on humans and the ecosystem throughout the SSA (Ripanda et al., 2021). The focused mitigation methods slowed down by this knowledge gap, which affects policy and decision-making. Moreover, the variety of socio- economic activities found in SSA countries, and the lack of analytical equipment and expertise contribute to the challenge of dealing with emerging micropollutants. Deficiency of analytical equipment such as ultra-performance liquid chromatography/tandem mass spectrometry (UPLC -MS) has been evident in the report of Global (2014), whereby out of 30 laboratories submitted in the year 2012 to 2013 nothing has been from the African continent. The study by Ssebugere et al. (2020), also, shows that only two countries (Kenya and South Africa) have afforded to analyze PFAS up to the year 2020 by using advanced equipment, while the rest depends on laboratories abroad.

Overcoming the challenges of PFAS in sub-Saharan Africa

Addressing the PFAS pollution in SSA demands a multidimensional approach beyond national boundaries. Governments, regulatory agencies, business associations, and academic institutions must work together to create solid regulatory frameworks, encourage environmentally friendly behavior, and stimulate the development of innovative PFAS cleanup methods appropriate for each region. Regarding this status, it is critical to provide communities with the knowledge and tools they need to recognize, reduce, and adjust to PFAS exposure (Gwenzi and Chaukura, 2018). Additionally, public health and environmental protection can be enhanced by initiatives that promote community-led solutions, safer alternatives, and increased awareness towards emerging pollutants (Ripanda et al., 2021). Therefore, SSA can effectively work together by promoting a collaborative commitment to research and policy innovation to address the PFAS challenges towards a more resilient and healthy future for its people and ecosystems.

Navigating regulatory guidelines for PFAS levels in SSA

Unlike SSA, other regions like the United States or the European Union have well-established monitoring guidelines and regulations for PFAS in drinking water and other environmental media. On the other hand, PFAS pollution and its possible health effects are globally known (Kurwadkar et al., 2022). Even though the impacts of PFAS are known, most SSA countries still need to develop guidelines and regulations to manage PFAS contamination. However, a few countries, such as South Africa, where PFAS contamination studies have been widely conducted, are developing such guidelines (Wee and Aris, 2023). In this regard, African nations may adopt the established standards by regional or international organizations such as the World Health Organization (WHO). The WHO has set a temporary recommended value of 500 ppt for total PFAS and 100 ppt for PFOA and PFOS individually (WHO, 2022) in drinking water. African countries should develop specific guidelines and regulations that comply with WHO recommendations. The developed guidelines should emphasize the multi-disciplinary approach for environmental agencies, health departments, regional research institutes, and international organizations to collaborate in carrying out investigations to determine PFAS status and recommend appropriate measures for addressing the challenge.

Conclusions

The literature reported the status of selected PFAS in the general environment of the SSA context. The level of PFAS detected in most of the environment, including drinking water, surface water, wastewater, rivers, dams, and aquatic organisms, have been reported. In aquatic environments, the levels of PFAS detected are mostly in picograms and nanograms units but lower than those detected in industrialized countries. It was noted that various factors contribute to the higher levels of PFAS issues in SSA, including industrial activities, agriculture activities and wastewater discharge in the receiving environment. Additionally, the importation of products containing PFAS, the use of firefighting foams containing PFAS at airports and military installations and improper disposal of electronic waste. Therefore, to address the challenge associated with PFAS in SSA, governments, environmental organizations, and researchers must work together to monitor, evaluate, and regulate these compounds. Moreover, raising awareness of the possible problems posed by PFAS and putting measures in place to prevent their escape into the environment is crucial in this process.

It was revealed that limited information exists in most Saharan countries on levels of PFAS part, with the most critical in the central African zone, making this review regarded as a partial value of the actual state of PFAS. Also, African countries need to develop analytical competencies and establish regulatory standards for PFAS levels in drinking water and other environmental media. Therefore, many studies should be conducted in SSA for critical justifications. To address the problem, international cooperation and knowledge sharing will also be essential because the production and use of PFAS in one part of the world could influence other regions distant from the source.

CRediT authorship contribution statement

Hildegard R. Kasambala: Writing – original draft, Conceptualization. **Mwemezi J. Rwiza:** Writing – review & editing, Supervision. **Nelson Mpumi:** Methodology, Formal analysis. **Mwema Felix Mwema:** Writing – review & editing. **Revocatus Machunda:** Writing – review & editing, Resources, Methodology, Conceptualization. **Kelvin Mtei:** Visualization. **Karoli N. Njau:** Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All relevant data are described in the manuscript.

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