

Per- and poly-fluoroalkyl substances in aquatic ecosystems and wastewater treatment works in Africa: Occurrence, ecological implications, and future perspectives

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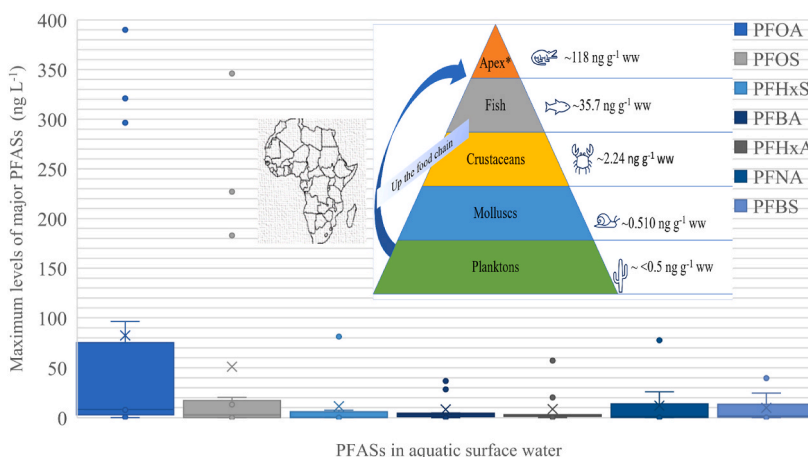
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HIGHLIGHTS

- PFAS levels vary widely with highest levels in ecosystems near urban areas.
- Urban run-off and WWTWs are dominant sources of PFASs in aquatic ecosystems.
- PFOA and PFHxS are the predominant PFASs in aquatic environments and WWTWs.
- Estimated RQs suggest organisms in rivers and marine systems are at a greater risk.
- Literature on temporal trends and ecological impacts of PFASs is scarce.

GRAPHICAL ABSTRACT



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ABSTRACT

The increasing levels of industrialization and urbanization have led to the generation of significant amounts of wastewater and waste products, often containing chemicals like per- and poly-fluoroalkyl substances (PFASs) commonly found in consumer products. PFASs are known for their persistence, ubiquity, and ecotoxicological impacts, raising concerns about potential harm to ecosystems. This paper reports the occurrence and evaluates the ecological risks of PFASs in aquatic ecosystems and wastewater treatment works (WWTWs) across Africa. We reviewed 32 papers published in the period 2009–2024 and identified a total of 35 PFAS compounds in surface waters, wastewater, sediments, fish, crocodiles, and invertebrates. Much of the reported studies came from South Africa, followed by Kenya and Nigeria. PFAS concentrations in Africa were <0.7 – 390.0 ng L⁻¹ in surface waters, 0.05 – 772 ng g⁻¹ dw in sediments, and <0.2 – 832 ng L⁻¹ in wastewater, while the highest levels in fish and invertebrates were 460.7 and 35.5 ng g⁻¹ ww, respectively. The PFAS levels were in the same range of data as those reported globally. However, the high concentrations of PFASs in sediments and wastewater suggest areas of point contamination and a growing risk to aquatic ecosystems from effluent discharges. Calculated risk quotients suggested that, in Africa, organisms in river systems face greater risks due to exposure to PFASs compared to those in lakes, while marine organisms might face higher risks compared to freshwater organisms. Future studies should focus on PFAS contamination sources, especially WWTWs, as emerging sources of PFASs in aquatic systems.

1. Introduction

Water is a vital natural resource that supports various ecosystems and sustains life on Earth (Connor, 2015). However, the rise in industrialization and urbanization processes has led to the generation of significant amounts of wastewater, which often contains various pollutants such as per- and poly-fluoroalkyl substances (PFASs) (Yadav et al., 2022). Examples of PFASs include perfluoroalkyl carboxylic acids (PFCAs), perfluoroalkyl sulfonic acids (PFSA), fluorotelomer substances (FTS) and fluorotelomer sulphonamides (FOSAs) (Buck et al., 2021). PFASs are highly stable and have both hydrophobic and hydrophilic parts making them amphiphilic (Evich et al., 2022; Lu et al., 2019), and therefore desirable for a range of applications. PFASs are commonly used as flame retardants, surfactants and surface protectors in industrial and consumer products, such as food packaging materials, fire extinguishing foams, paints, aircraft sprays, lubricants, non-stick cookware, personal care products, and waterproof clothes (Bui et al., 2024; Glüge et al., 2020; Kurwadkar et al., 2022).

In the environment, consumer products containing PFASs ultimately become waste after use and may accumulate at dumping sites and landfills or find their way to water resources via runoff (Lenka et al., 2021). In addition, PFASs may enter wastewater treatment works (WWTWs) from commonly used household and office consumer products through the sewer system (Kwon et al., 2017). Degradation products of PFASs may also be synthesized from their precursors during treatment processes leading to their discharge into receiving water ecosystems and may pose health risks to aquatic organisms (Zhang et al., 2021).

Numerous studies have reported adverse effects of PFASs in aquatic organisms such as plankton, aquatic vertebrates, invertebrates, and microorganisms (Hamid et al., 2018; Ma et al., 2022; Sinclair et al., 2020; Spyrou et al., 2024; Yu et al., 2023). For instance, zebrafish embryos exposed to PFOS at concentrations as low as 0.0006 mg L⁻¹ exhibited developmental delays, reduced larval survival, and altered sex ratios (Sinclair et al., 2020). Exposure of zebrafish to PFOA and PFOS led to heritable behavioural dysregulation and lipid pathway gene expression disruption, with morphological abnormalities appearing in later generations (Haimbaugh et al., 2022). In amphibians, exposure to PFASs caused significant mortality in bullfrog larvae, while northern leopard frogs showed delayed metamorphosis and growth defects like reduced tadpole length (Sinclair et al., 2020). In aquatic invertebrates, PFOS exposure induced oxidative stress, DNA damage, and membrane instability in green mussels, triggered apoptosis and tissue damage in pearl mussels, and reduced filtration rates and enzyme activity in Asian clams (Ma et al., 2022).

Generally, WWTWs are pivotal in removing contaminants before

they reach the receiving environment. However, available conventional wastewater treatment methods which rely on biological and physico-chemical degradation, and oxidation are inefficient in removing emerging organic pollutants such as pharmaceuticals and PFASs (Qu et al., 2020; Shehu et al., 2022). This is because PFASs have unique chemical properties, such as strong carbon-fluorine bonds, which make the chemicals highly resistant to degradation and thus, persistent in wastewater effluent (Lu et al., 2019). Additionally, new PFASs can be synthesized during biological treatment, raising their influx in the effluents if their precursors are present, decelerating treatment efficiencies of WWTWs using conventional methods (Dalahmeh et al., 2020). Recent technologies, such as advanced oxidation processes, photocatalysis, adsorption and membrane technology, have demonstrated higher PFAS removal rates, offering potential solutions for improving treatment efficacy (Adewuyi and Li, 2024).

Evaluating PFASs in WWTWs relative to aquatic ecosystems is crucial for assessing ecological risks in receiving water systems (Lenka et al., 2021). However, while global studies have reported ecological risks posed by PFASs from WWTW effluents to water bodies (Yadav et al., 2022), a critical synthesis of the available literature in Africa is missing. Developing countries in Africa are often dumping sites for electronic and household wastes from the developed world (Baguma et al., 2023). Such waste is a potential source of contaminants, such as PFASs. In addition, sub-Saharan Africa is undergoing rapid urbanisation and industrialization implying a surge in the emission of industrial and urban wastes that could also contain PFASs and related pollutants. Hence, there is a need to review past studies to identify PFAS trends and provide perspectives for future research directions (Lenka et al., 2021). This review aimed at synthesising the available literature about PFASs in WWTWs and aquatic environments in Africa, assessing ecological risks, and proposing future research directions based on identified gaps.

2. Materials and methods

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure rigor in data collection, screening and synthesis (Page et al., 2021). In this study, the literature search was conducted through six key scholarly databases (Wiley Online Library, Scopus, Science Direct®, Web of Science, PubMed, and Google Scholar) using specific phrases like 'Per- and polyfluoroalkyl substances in Africa', 'PFASs in wastewater AND Africa', 'PFASs in wastewater treatment plants AND Africa', or 'PFASs ecological risks in Africa', alongside variations specific to freshwater bodies or country names in Africa. These phrases were complemented by keywords such as 'freshwater', 'environment', 'surface water', 'lakes', 'rivers', 'sludge', 'wastewater', 'sediments', 'fish', 'invertebrates',

'reptiles', and 'ecosystem.' A supplementary search was conducted using broader terms such as 'contaminants of emerging concern' or 'endocrine disrupting chemicals' and 'perfluorinated organic pollutants', 'perfluoroalkyl acids', 'PFCAs', 'PFOS', 'PFOA' or 'persistent organic compounds, POPs' instead of 'PFASs.'

The selection process adhered to predefined inclusion and exclusion criteria. Studies were included if they focused on PFAS occurrence, ecological impacts, and removal efficiency in African aquatic ecosystems and WWTWs, published in English between 2009 and 2024. This period was considered because PFASs (PFOS and PFOA) were first added onto the list of banned chemicals by the Stockholm Convention in 2009. We excluded articles that did not address PFASs or were outside the review's geographical and thematic focus. All identified studies were first screened based on title and abstract, before full texts were reviewed to assess relevance. The selection process, and the number of studies considered at each stage, is illustrated in the PRISMA flowchart below (Fig. 1).

In total, 32 studies met the inclusion criteria. For consistency and comparability, PFAS concentrations across studies were standardized, with most levels reported in nanograms per litre (ng L^{-1}) for water and nanograms per gram dry weight ($\text{ng g}^{-1} \text{ dw}$) for sediments. Appropriate conversions were made for other units such as pg g^{-1} .

3. Results & discussion

3.1. Occurrence of PFASs in aquatic ecosystems in Africa

As of April 2024, PFASs had been studied in 11 African countries. The highest number of studies have been conducted in South Africa (12 studies), followed by Kenya (6), Nigeria (5), Uganda (3), Ghana (2), Ethiopia (1), Mozambique (1), Tanzania (1), Zambia (1), Mali (1), and Tunisia (1). South Africa has more advanced laboratory facilities and research infrastructure, which may have enabled the production of a greater volume of PFAS-related studies, particularly in the context of aquatic ecosystems (Ssebugere et al., 2020). The identified studies were also mostly from countries in sub-Saharan Africa, potentially because North Africa is dominated by the Saharan desert, limiting the number of

aquatic bodies, and corresponding literature on PFASs in aquatic ecosystems. Most of the studies that investigated PFASs in the aquatic ecosystem reported them in surface water (23 studies), followed by sediments (11), fish (9) and invertebrates (2), with PFOA and PFOS as most dominant (Fig. S1).

A total of 33 unique PFASs have been reported in aquatic ecosystems across the African continent. Five of the reported PFASs are short-chain compounds; Perfluorobutanesulfonic acid (PFBS), Perfluorobutanoic acid (PFBA), Perfluoropentanoic acid (PFPeA), Perfluorohexanoic acid (PFHxA) and Perfluoropentanesulfonic acid (PFPeS). The remaining 27 compounds reported are long chain PFASs; Perfluoroheptanesulfonic acid (PFHpS), Perfluorohexanesulfonic acid (PFHxS), Perfluoroheptanoic acid (PFHpA), Perfluorononanesulfonic acid (PFNS), Perfluorononanoic acid (PFNA), Perfluorodecanoic acid (PFDA), Perfluorododecanoic acid (PFDoDA), Perfluoroundecanoic acid (PFUnDA), Perfluorooctanesulfonic acid (PFOS), Perfluorooctanoic acid (PFOA), Perfluorodecanesulfonic acid (PFDS), Ethyl perfluorooctanesulfonamidoacetic acid (EtFOSAA), Perfluorobutanesulfonic acid (PFBS), Perfluoroheptanesulfonic acid (PFHpS), 1H,1H,2H,2H-perfluoro-1-hexanesulfonate (4:2FTS), 1H,1H,2H,2H-perfluoro-1-octanesulfonate (8:2FTS), Perfluoropentanesulfonic acid (PFPeS), Perfluorooctanesulfonamide (FOSA), Perfluorohexanesulfonic acid (FHxSA), Methyl perfluorooctanesulfonamidoacetic acid (MeFOSAA), Perfluoro-1-butanefluoramide (FBSA), 6:2 Fluorotelomersulfonate (6:2FTSA), Hexafluoropropylene oxide dimer acid (GenX), Dodecafluoro-3H-4,8-dioxananoate (ADONA), Potassium 9-chlorohexadecafluoro-3-oxonane-1-sulfonate (PFONs), Perfluorononanesulfonic acid (PFNs), Potassium 11-chloroeicosafluoro-3-oxaundecane-1-sulfonate (PFOUNDs), and 6:2 Fluorotelomersulfonate (PFONS).

Of the 33 PFASs reported, seven have established Environmental Quality Standards (EQSs) and the remaining 26 are without EQSs. The reported PFASs in Africa account for 9.3% of the 256 commercially relevant PFASs in the environment and 0.70% of the 4730 listed datasets from the manufacturing industry (Buck et al., 2021).

In Africa, the major sources of PFASs in the ecosystems reported include municipal landfills, wastewater treatment plants, industrial wastewater, urban runoff and consumer products (Ssebugere et al.,

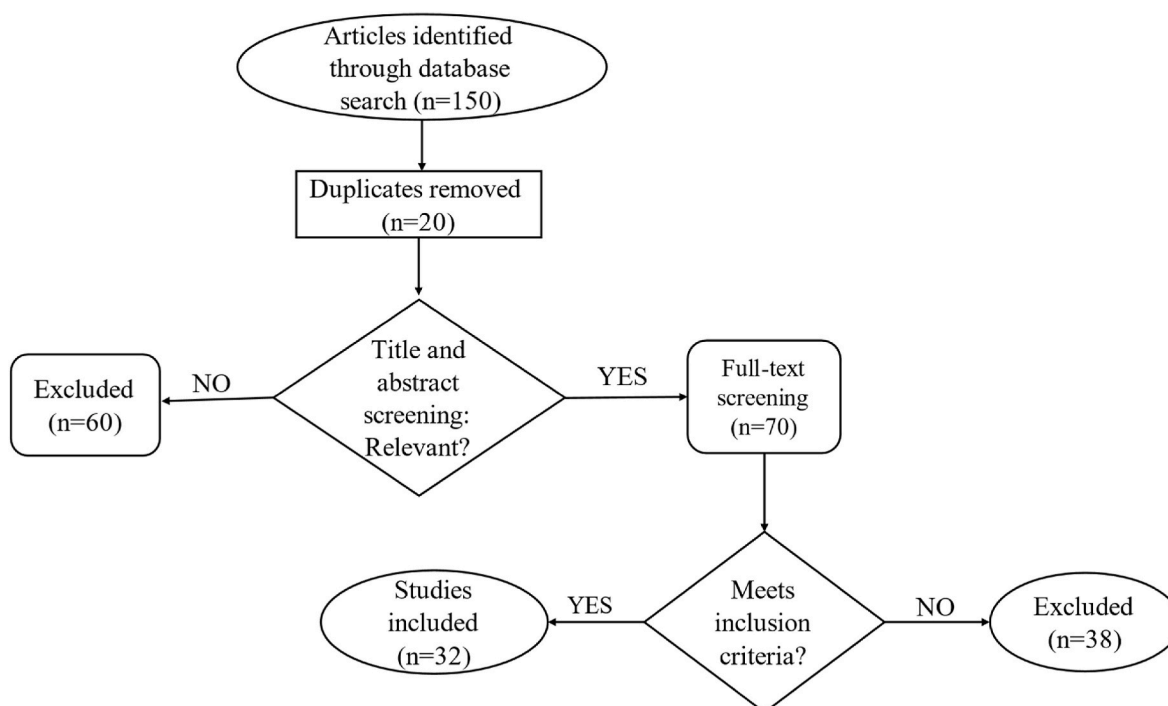


Fig. 1. Flow chart showing the article selection process.

2020). PFAS-containing products, including cosmetics, textiles, and fire-extinguishing foams, eventually enter wastewater and aquatic systems through various pathways, thus contributing to the PFAS burden (Bui et al., 2024). Recent global studies have also highlighted that dust particles and microplastics serve as vectors for PFAS transport into ecosystems (Elnakar et al., 2024; Ismail et al., 2023). Across sub-Saharan Africa, there is a significant variation in PFAS concentrations, with hotspots observed near urban centres and industrial zones (Kasambala et al., 2024).

3.1.1. PFASs in surface water

Surface waters have been the most analysed media for PFASs in aquatic ecosystems across Africa. The pioneering study by Orata et al. (2009) reported PFOA and PFOS levels ranging between 0.4 and 96.4 ng L⁻¹ in the Kenyan side of Lake Victoria (Table 1). The tributary rivers had higher levels (~96.4 ng L⁻¹) than the lake water (~11.6 ng L⁻¹), suggesting generalized point sources such as domestic and industrial waste (Orata et al., 2009). Ololade (2014) and Mudumbi et al. (2014a,b) reported PFOS levels of 16.19 and 182 ng L⁻¹, in rivers in Nigeria and South Africa, respectively (Table 1). These PFOS levels in rivers exceeded the 0.23 ng L⁻¹ threshold value for highly conserved freshwater systems (Groffen et al., 2021). These pioneering studies collectively reported higher levels in rivers than in lakes possibly due to the dilution effect, and a greater emphasis on legacy PFASs. A similar trend was observed in studies that followed, reporting higher levels of both PFOS and PFOA in the range of <1.0–390 ng L⁻¹ (Bangma et al., 2017; Essumang et al., 2017; Shafique et al., 2016; UNEP, 2017; Verhaert et al., 2017) in rivers than in lakes (e.g., ~5.6 ng L⁻¹ as reported by Ahrens et al., 2016).

Recent studies have expanded the scope of PFAS analysis by examining both legacy and emerging PFASs (Table 1). For instance, Groffen et al. (2018) investigated 15 PFAS compounds in the water of the Vaal River in South Africa. The authors found PFOS as the most dominant compound. The study also reported biomagnification of PFBA and PFTrDA, likely due to their higher persistence. In the study, Groffen et al. (2018) reported average levels of total PFASs in three rivers from South Africa as below limit of quantification (<LOQ) to 38.5 ng L⁻¹. The levels were a magnitude lower than those in other rivers within the same region; 12.8–296.48 ng L⁻¹ (Batayi et al., 2021; Fagbayigbo et al., 2018). The PFAS levels in South Africa were also higher than those in surface waters in Uganda (0.01–3.64 ng L⁻¹) and Kenya (0.16–3.01 ng L⁻¹) as reported by Arinaitwe et al. (2021) and Chirikona et al. (2022), respectively. The difference in PFAS concentrations across regions is probably due to the higher level of urbanisation in South Africa which may increase the flux of PFAS-contaminated materials disposed of in river systems. Remarkably, the available studies (Table 1) indicate higher PFAS levels in certain areas of Lake Victoria, Diep River, and Nairobi River, suggesting potential localized sources probably due to the neighbouring urban centres.

3.1.2. PFASs in sediments

In addition to being aquatic habitats, sediments can act as reservoirs of pollutants, thus may expose them to benthic organisms. Sediment characteristics, such as organic carbon content and mineral composition, can influence the adsorption capacity of PFASs (Bui et al., 2024). Few studies (n = 11) have investigated the levels of PFASs in sediments in Africa. Elevated levels of PFASs have been reported with maximum concentrations of up to 772 ng g⁻¹ dry weight (dw). Due to their adsorption capabilities, the levels of PFASs in sediments are higher than those in surface water.

As shown in Table 2, PFOA and PFOS were the most reported and dominant PFASs with levels <99.1–187 and <LOQ–121 ng g⁻¹ dw, respectively (Ahrens et al., 2016; Chirikona et al., 2022; Fagbayigbo et al., 2018; Fauconier et al., 2020; Ololade, 2014; Ololade et al., 2018). The highest levels of PFOA in sediments in Africa have been reported in Diep River, South Africa (~772 ng g⁻¹ dw; Mudumbi et al., 2014a,b),

and Lake Victoria, Kenya (~99.1 ng g⁻¹ dw, Orata et al., 2011).

Like surface water, the existing literature shows that the levels of PFASs in sediments were higher in South Africa than in other parts of Africa. In addition, river sediments have shown significantly higher levels of PFASs than lake sediments possibly due to their proximity to pollution sources, dynamic flow conditions, efficient sorption and partitioning, surface runoff, and influence from wastewater treatment plants (Orata et al., 2011).

3.1.3. PFASs in aquatic organisms

Aquatic organisms, including fish, invertebrates, and crocodiles, have been assessed for the presence of PFASs in their bodies (Tables 1 and 2). In fish, PFOS and PFOA were first reported in Nile perch and Tilapia from the Winam Gulf of Lake Victoria, East Africa, with levels reaching 12.4 and 35.7 ng g⁻¹ wet weight (ww), respectively (Francis et al., 2008). PFOS levels were several orders of magnitude higher in the liver (1.40–35.70 ng g⁻¹ ww) than in muscles (0.90–12.40 ng g⁻¹ ww). This indicated a higher bioaccumulation of PFASs in metabolic body tissues such as the liver. In a related study, Ahrens et al. (2016) assessed PFAS levels in fish from Lake Tana. Total (Σ) PFAS levels ranged from below limit of detection (<LOD) to 5.8 ng g⁻¹ ww, with PFDA present in all the species. PFCAs (PFBA, PFHxA, PFNA, PFDA, PFUnDA) were predominant in fish (71%) compared to corresponding water samples (68%), and PFASs (PFHxS and PFOS) (Ahrens et al., 2016). This trend might be due to the solubility and thus higher bioaccumulation potential of PFCAs or the degradation of PFASs by chemosynthetic bacteria that feed on sulfur.

PFASs were also detected in the plasma of Nile crocodiles. PFOS was the dominant compound with levels up to 118 ng g⁻¹ ww (Christie et al., 2016). The high levels of PFOS in crocodiles suggest that organisms higher in the food chain tend to bio-accumulate and -magnify PFASs. Fish from the Ugandan and Kenyan side of Lake Victoria had PFOS levels (<35.5 ng g⁻¹ ww) far much less than those from Mississippi River (3.0–760 ng g⁻¹ ww) (Newsted et al., 2017). The higher levels in the latter may be attributed to the higher urbanisation in United States of America.

In South Africa, Groffen et al. (2018) reported biomagnification of highly persistent compounds PFDA and PFTrDA in fish from the Vaal River. Levels of Σ PFASs were up to 34.0 ng g⁻¹ ww. Most recently, Barhoumi et al. (2022) assessed 21 legacy and emerging PFASs in nine aquatic species (three fish, two crustaceans, and four molluscs) in the marine waters of the Bizerte Lagoon, Tunisia, North Africa. Out of these, 12 PFASs including PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA, PFHxS, PFTeDA, PFOS, and 6:2 FTS, were detected in the samples. The Σ PFAS levels ranged from 0.202 to 2.89 ng g⁻¹ dw, with higher levels detected in crustaceans (mean 2.24 ng g⁻¹ dw) than in fish (0.751 ng g⁻¹ dw) and molluscs (0.510 ng g⁻¹ dw).

Overall, PFOA emerges as the most prevalent PFASs in African aquatic ecosystems, exhibiting the highest levels and bioaccumulation/biomagnification potential in aquatic organisms across the continent. The levels of PFOS were comparable to those in more developed and/or industrialized countries, such as China (Huang et al., 2018; Jin, 2006; 2009) (Table S1). The high PFOA levels in Africa have been attributed to the size of the catchment area with a high influx of surface water run-off, WWTWs, landfills, waste disposal sites, and irrigation schemes using PFASs-related products (Mudumbi et al., 2014a,b; Ekperusi et al., 2023). Variations in PFAS levels were mostly due to urbanisation disparities across several regions and aquatic systems (Ahrens et al., 2016; Batayi et al., 2021). Moreover, seasonal variations appeared to be influenced by the level of human activities and climate-dependent usage of PFAS-containing products (Bangma et al., 2017).

3.2. Occurrence of PFASs in WWTWs across Africa

To date, six studies have reported over 27 PFASs in wastewater treatment works (WWTWs) across Africa (Table S2). Of these, 19

Table 1

Occurrence of PFASs with EQS in aquatic systems across Africa.

PFASs	Surface water EQS (ng L ⁻¹)	Concentration (ng L ⁻¹)	Aquatic ecosystem(s)	Country	Authors
PFOA	<19000 ng L ⁻¹ ; highly conserved	<0.28–0.69 86.2–321 0.16–3.01	Lake Tana Pra and Kakum river Nairobi river basin	Ethiopia Ghana Kenya	Ahrens et al. (2016) Essumang et al. (2017) Chirikona et al. (2022)
	>632000 ng L ⁻¹ ; highly disturbed	1.6–8.8 <0.4–11.65 0.4–96.4 0.8–11.1 0.6–390 29.46–296.5 <LOD–0.063 2.4–4.1 <LOD–0.6 0.46–7.78 0.42–2.95	River Sosiani Lake Victoria Gulf (lake) Lake Victoria Gulf (river) various rivers Multiple rivers*a Hartbeespoort and Roodeplaat dam Indian Ocean Nakivubo wetland Lake Victoria River Kagera & Sio Open Lake (Victoria)	Kenya Kenya Kenya Nigeria South Africa South Africa Tanzania Uganda Uganda Uganda Uganda	Shafique et al. (2016) Orata et al. (2009) Orata et al. (2009) Ololade et al. (2018) FGM Batayi et al. (2021) Hope (2020) Dalahmeh et al. (2020) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021)
PFOS	<0.23 ng L ⁻¹ ; highly conserved	<0.05–0.22 77.2–227	Lake Tana Pra and Kakum river	Ethiopia Ghana	Ahrens et al. (2016) Essumang et al. (2017)
	>2000 ng L ⁻¹ highly disturbed	<0.4–2.53 0.01–1.37 0.4–13.23 4.7* LOQ–0.141 3.9–20.4 1.71–16.19 <0.4–183 5.35–346.3 LOQ–0.73 2.0–3.1 <LOD <0.04–0.23 0.01–0.06 0.023–1.2 LOQ–0.0254 <LOQ–7.6 18.31–81.18 0.5–0.9 0.01–0.07 <LOD–0.03 <LOD <0.05–2.8 0.6–0.7 0.74–4.79 10.2–28.4 10.86–36.79 <LOD 1.34–3.66 <LOD–3.87 0.76–1.62 <LOD <0.05–1.3 BDL–0.06 0.15–3.0 1.3–2.5 <LOQ–1.8 2.36–57.19 <LOQ–20.3 1.8–2.4 0.21–2.35 0.87–2.89 0.2–0.3 <0.05–0.17 8.6–25.9 0.06–1.39 <LOQ–1.8 1.39–77.56 0.6–0.7 0.13–1.36 <LOD–0.26 <LOD–0.1 0.01–1.0 <LOQ–24.7 8.54–39.71 0.7–1.7 0.05–0.13 0.02–0.11 <LOD–2.3	Lake Victoria Gulf (lake) Nairobi river basin Lake Victoria Gulf (rivers) Niger river Indian Ocean various rivers Southwest rivers Multiple rivers*a Hartbeespoort/Roodeplaat dam Olifants river Nakivubo wetland Lake Victoria River Kagera & Sio Open Lake (Victoria) Lake Tana Indian Ocean Vaal river Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Plankenburg river Hartbeespoort/Roodeplaat dam Lake Victoria River Kagera River Sio Open Lake (Victoria) Nakivubo wetland Lake Tana Pra and Kakum river Nairobi river basin River Sosiani Vaal river Hartbeespoort and Roodeplaat dam Vaal River Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria	Kenya Kenya Kenya Mali Mozambique Nigeria Nigeria South Africa South Africa South Africa Uganda Uganda Uganda Uganda Uganda Mozambique South Africa South Africa Uganda Uganda Uganda Uganda Ethiopia Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Ethiopia Ghana Kenya Kenya South Africa South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda	Orata et al. (2009) Chirikona et al. (2022) Orata et al. (2009) UNEP (2017) Hope (2020) Ololade et al. (2018) Ololade (2014) FGM Batayi et al. (2021) Verhaert et al. (2017) Dalahmeh et al. (2020) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Ahrens et al. (2016) Hope (2020) Groffen et al. (2018) Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Dalahmeh et al. (2020) Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) Fagbayigbo et al. (2018) Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Ahrens et al. (2016) Essumang et al. (2017) Chirikona et al. (2022) Shafique et al. (2016) Groffen et al. (2018) Batayi et al. (2021) Groffen et al. (2018) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020)
PFHxS	<0.23 ng L ⁻¹ ; highly conserved	0.023–1.2 LOQ–0.0254 <LOQ–7.6 18.31–81.18 0.5–0.9 0.01–0.07 <LOD–0.03 <LOD <0.05–2.8 0.6–0.7 0.74–4.79 10.2–28.4 10.86–36.79 <LOD 1.34–3.66 <LOD–3.87 0.76–1.62 <LOD <0.05–1.3 BDL–0.06 0.15–3.0 1.3–2.5 <LOQ–1.8 2.36–57.19 <LOQ–20.3 1.8–2.4 0.21–2.35 0.87–2.89 0.2–0.3 <0.05–0.17 8.6–25.9 0.06–1.39 <LOQ–1.8 1.39–77.56 0.6–0.7 0.13–1.36 <LOD–0.26 <LOD–0.1 0.01–1.0 <LOQ–24.7 8.54–39.71 0.7–1.7 0.05–0.13 0.02–0.11 <LOD–2.3	Lake Tana Indian Ocean Vaal river Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Plankenburg river Hartbeespoort/Roodeplaat dam Lake Victoria River Kagera River Sio Open Lake (Victoria) Nakivubo wetland Lake Tana Pra and Kakum river Nairobi river basin River Sosiani Vaal river Hartbeespoort and Roodeplaat dam Vaal River Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria	Ethiopia Mozambique South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Ethiopia Ghana Kenya Kenya South Africa South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda	Ahrens et al. (2016) Hope (2020) Groffen et al. (2018) Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Dalahmeh et al. (2020) Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) Fagbayigbo et al. (2018) Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Ahrens et al. (2016) Essumang et al. (2017) Chirikona et al. (2022) Shafique et al. (2016) Groffen et al. (2018) Batayi et al. (2021) Groffen et al. (2018) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020)
PFBA	LOAEL: 4.7 × 10 ⁵ NOAEL: 4.7 × 10 ⁵	<0.05–2.8 0.6–0.7 0.74–4.79 10.2–28.4 10.86–36.79 <LOD 1.34–3.66 <LOD–3.87 0.76–1.62 <LOD <0.05–1.3 BDL–0.06 0.15–3.0 1.3–2.5 <LOQ–1.8 2.36–57.19 <LOQ–20.3 1.8–2.4 0.21–2.35 0.87–2.89 0.2–0.3 <0.05–0.17 8.6–25.9 0.06–1.39 <LOQ–1.8 1.39–77.56 0.6–0.7 0.13–1.36 <LOD–0.26 <LOD–0.1 0.01–1.0 <LOQ–24.7 8.54–39.71 0.7–1.7 0.05–0.13 0.02–0.11 <LOD–2.3	Lake Tana River Sosiani Nairobi river basin Plankenburg river Hartbeespoort/Roodeplaat dam Lake Victoria River Kagera River Sio Open Lake (Victoria) Nakivubo wetland Lake Tana Pra and Kakum river Nairobi river basin River Sosiani Vaal river Hartbeespoort and Roodeplaat dam Vaal River Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria	Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Ethiopia Kenya Kenya South Africa South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda	Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) Fagbayigbo et al. (2018) Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Ahrens et al. (2016) Essumang et al. (2017) Chirikona et al. (2022) Shafique et al. (2016) Groffen et al. (2018) Batayi et al. (2021) Groffen et al. (2018) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020)
PFHxA	LOAEL: 4.4 × 10 ⁵ NOAEL: 2.1 × 10 ⁵	<0.05–1.3 BDL–0.06 0.15–3.0 1.3–2.5 <LOQ–1.8 2.36–57.19 <LOQ–20.3 1.8–2.4 0.21–2.35 0.87–2.89 0.2–0.3 <0.05–0.17 8.6–25.9 0.06–1.39 <LOQ–1.8 1.39–77.56 0.6–0.7 0.13–1.36 <LOD–0.26 <LOD–0.1 0.01–1.0 <LOQ–24.7 8.54–39.71 0.7–1.7 0.05–0.13 0.02–0.11 <LOD–2.3	Lake Tana Pra and Kakum river Nairobi river basin River Sosiani Vaal river Hartbeespoort and Roodeplaat dam Vaal River Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria	Ethiopia Ghana Kenya Kenya South Africa South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Ethiopia Kenya Kenya South Africa South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda	Ahrens et al. (2016) Essumang et al. (2017) Chirikona et al. (2022) Shafique et al. (2016) Groffen et al. (2018) Batayi et al. (2021) Groffen et al. (2018) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020)
PFNA	LOAEL: 2.9 × 10 ⁴ NOAEL: 2.2 × 10 ⁴	<0.05–0.17 8.6–25.9 0.06–1.39 <LOQ–1.8 1.39–77.56 0.6–0.7 0.13–1.36 <LOD–0.26 <LOD–0.1 0.01–1.0 <LOQ–24.7 8.54–39.71 0.7–1.7 0.05–0.13 0.02–0.11 <LOD–2.3	Lake Tana River Sosiani Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Lake Tana River Sosiani Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria	Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Ethiopia Kenya Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda	Ahrens et al. (2016) Shafique et al. (2016) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020) Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020)
PFBS	LOAEL: 1.1 × 10 ⁶ NOAEL: 64 × 10 ⁵	0.01–1.0 <LOQ–24.7 8.54–39.71 0.7–1.7 0.05–0.13 0.02–0.11 <LOD–2.3	Nairobi river basin Multiple rivers*a Hartbeespoort/Roodeplaat dam Nakivubo wetland River Kagera & Sio Open Lake (Victoria) Lake Victoria	Kenya South Africa South Africa Uganda Uganda Uganda Uganda Uganda	Chirikona et al. (2022) FGM Batayi et al. (2021) Dalahmeh et al. (2020) Arinaitwe et al. (2021) Arinaitwe et al. (2021) Dalahmeh et al. (2020)

Multiple rivers*a = Olifants, Eerste, Diep, Plankenburg and Vaal Rivers; FGM = Fagbayigbo et al. (2018), Groffen et al. (2018), Mudumbi et al. (2014a,b); * mean ng g⁻¹ dw values reported; <LOQ = below limit of quantification (LOQs are not reported); <LOD = below limit of detection; dw = dry weight; ww = wet weight.

compounds were found in significant concentrations, all surpassing the levels observed in surface water systems. The total PFAS concentrations in WWTWs also appeared to be increasing with increasing levels of urbanisation. Lower levels of PFASs were found in less urbanised locations of Kenya and Nigeria compared to the highly urbanised areas of South Africa.

In West Africa, [Sindikou et al.](#), reported levels of PFASs in sludge from nine WWTWs in Nigeria with levels varying from 10 to 597 (PFCAs) and 14 to 540 (PFASs) pg g^{-1} dw. PFOS, PFOA, PFNS, PFDA, and PFUnDA were the dominant contaminants, and the authors attributed the PFASs to industrial, municipal and hospital wastewater treatment facilities. In East Africa, [Chirikona et al. \(2015\)](#) reported PFASs influx into Lake Victoria originating from the sludge and wastewater in nine WWTWs near the lake. PFOA and PFOS were the most prevalent, with respective concentrations between 1.3 and 28 ng L^{-1} and 0.9–18.8 ng L^{-1} in wastewater, and 117–673 pg g^{-1} dw and 98–683 pg g^{-1} dw in sludge samples. The study revealed a significant relationship between urbanization and PFASs daily discharge into the lake and highlighted the need for further investigation of PFAS load in other urban locations near the lake, such as Kampala and Mwanza ([Chirikona et al., 2015](#)).

In Uganda, a recent study by [Dalahmeh et al. \(2020\)](#) investigated the levels of 26 PFASs in Bugolobi WWTW. Ten (10) PFASs were detected in effluent wastewater with levels ranging from 5.4 to 9.1 ng L^{-1} and PFHxS was the dominant compound. Notably, the authors reported suboptimal removal of PFASs during the water treatment process as the PFAS levels in the effluents exceeded those in influents. This may indicate the synthesis of new PFASs from their precursors during WWTW processes, such as biodegradation, photolysis and hydrolysis ([Zhang et al., 2021](#)).

In South Africa, three studies identified PFOA, PFOS, PFNA, PFBS, and FOET as the prevalent contaminants in WWTWs. Total PFAS levels varied from 61 to 3327 ng L^{-1} for influents and 2.35–7699 ng L^{-1} for effluents ([Adeleye, 2016](#); [Kibambe et al., 2020](#); [Morethe et al., 2024](#)). The earliest study by [Adeleye \(2016\)](#), reported the occurrence of six PFAS compounds in four WWTWs. The total PFAS concentrations in influents and effluents were 66.04 ng L^{-1} and 2.35 ng L^{-1} at Beaufort West, 66.05 ng L^{-1} and 23.13 ng L^{-1} at Zandvliet, 73.65 ng L^{-1} and 35.28 ng L^{-1} at Bellville, and 13.49 ng L^{-1} and 6.16 ng L^{-1} at Scottsdene, respectively. PFNA was the predominant contaminant (23.4%), followed by PFOA (20.3%), PFHpA (18.8%), PFUnDA (18.75%), PFDA (10.9%) and PFOS (7.8%) being the least ([Adeleye, 2016](#)). Moreover, PFOS was not detected at two WWTWs (Beaufort West and Zandvliet), despite being a legacy dominant PFAS amongst the WWTWs. This might be due to a reduced usage of PFSA products compared to PFCAs in these areas ([Batayi et al., 2021](#)).

Generally, higher total PFAS levels have been reported in the most recent studies. For instance, [Kibambe et al. \(2020\)](#) reported seven PFASs (Table S2) in influents of three WWTWs of South Africa. Long-chain (L) PFOS dominated the PFASs with a maximum concentration of 508 ng L^{-1} . The total levels in effluents were 224.4, 76.5, and 35.8 ng L^{-1} at Daspoort, Phola and Zeekoegat WWTWs, respectively. Furthermore, long-chain PFASs (such as L-PFOS) showed better removal efficiencies (80–94%) than short-chain congeners (<39%), suggesting increased resistance in shorter-chain PFASs ([Kibambe et al., 2020](#)). Recently, [Morethe et al. \(2024\)](#) reported the $\sum$ PFAS levels recorded since 2008 in the WWTWs of Mpumalanga, Limpopo, Northern Cape, Northwest, Free State and KwaZulu-Natal in South Africa. The $\sum_{21}$ PFASs in influents and effluents ranged from 137 to 3327 ng L^{-1} and 265–7699 ng L^{-1} , respectively, in the dry season and 61–2953 ng L^{-1} and 171–3458 ng L^{-1} in the wet season. PFOA and L-PFBS had the highest mean concentrations of 586 ng L^{-1} and 552 ng L^{-1} , respectively, during the dry season, while FOET and PFNA were 1,399 ng L^{-1} and 811 ng L^{-1} during the wet season ([Morethe et al., 2024](#)). These unusual recent elevated levels could be attributed to local PFAS-producing companies in South Africa, increased importation, or poor wastewater treatment efficiencies.

In general, there is an increasing trend in the PFAS levels measured

in WWTWs across Africa over the past two decades. Due to differences in the levels of urbanisation, the concentrations of PFASs reported in WWTWs in South Africa are much higher than those reported in Uganda, Kenya, and Nigeria (Table S1). The total levels of PFASs in effluents (2.35–7699 ng L^{-1}) are also much higher than those in surface water systems (2.0–772 ng L^{-1}), indicating a tenfold increase in PFASs levels discharged into aquatic ecosystems compared to initial levels in the surface water ([Huang et al., 2018](#); [Jin, 2006](#); [2009](#)). The available literature suggests that aquatic systems face PFAS contamination from diverse sources including direct discharges, urban runoffs, and WWTWs ([Ahrens and Bundschuh, 2014](#); [Ssebugere et al., 2020](#)).

The disparity in PFAS occurrence and abundance between WWTWs and aquatic systems across different regions in Africa could also be attributed to differences in the types of PFAS-containing products used in various regions. Other factors include varied efficiencies of treatment processes in different regions, differences in half-lives and transport mechanisms within the aquatic environment, or differences in laboratory facilities and the nature of standards used during analysis ([Ankley et al., 2021](#)). Importantly, while there are 4730 known PFASs, the development of methods and standards for analysing all of them is still on-going. Moreover, the 2018 OECD/UNEP Report reveals that out of the 4,730 compounds known globally, only a small subset of 256 are commercially relevant and these account for roughly 5.5% of all PFASs. Responsible authorities may want to prioritize certain PFASs based on known environmental risks or regulatory requirements ([Buck et al., 2021](#)).

3.3. Levels of PFASs in aquatic ecosystems across Africa in comparison to established environmental quality standards (EQSs)

Generally, environmental quality standards (EQSs) for PFASs on non-human biota (e.g., aquatic organisms) are still scarce, as most regulatory attention predominantly focuses on human health risks posed by PFASs-contaminated drinking and groundwater ([Ankley et al., 2021](#)). At present, environmental safety levels for only a limited number of PFASs (PFOS, PFOA, PFBS, PFHxS, PFBA, PFHxA, PFNA) are documented ([Groffen et al., 2021](#)). The levels of PFOS in surface water in Africa (<346.33 ng L^{-1}) were generally below the European Union's PFOS-EQS (maximum-allowable-concentration as 36,000 ng L^{-1}) for freshwater habitats but surpassed safe thresholds (0.23 ng L^{-1}) for highly conservation systems ([Groffen et al., 2021](#)). This suggests that these concentrations could pose a risk to systems that are of ecological conservation priority. Similarly, the maximum PFOA levels in aquatic water systems in Africa, were up to 390 ng L^{-1} in surface water (Tables 1 and 2), but below EQS (19,000 ng L^{-1}), possibly due to the lower levels of industrialization.

In Africa, PFNA had concentrations (<LOD–77.56 ng L^{-1}) below the EQS_{PFNA} thresholds (2,200 ng L^{-1}) for the no-observed adverse effect level (NOAEL) and 2,900 ng L^{-1} for the lowest observed adverse effect level (LOAEL) ([Zodrow et al., 2020](#)). The NOAEL and LOAEL are water risk-based screening levels for aquatic wildlife derived from controlled laboratory experiments involving various species of aquatic organisms (aquatic plants, invertebrates, fish, and amphibians). These levels focus on endpoints such as growth, survival, mortality, reproduction, and development ([Divine et al., 2020](#)). EQS thresholds were established for surface water to determine the acute and chronic toxicity of PFASs. Concentrations of PFNA in Africa can be considered safe, although the ubiquity of the compound (Table 1) in aquatic environments suggests potential areas of concern. The levels of PFHxS (<LOQ–81.18 ng L^{-1}) exceed EQS (0.23 ng L^{-1}) for high conservation systems suggesting a probable risk posed. Therefore, sulphonic acids appear to be of more concern than carboxylic acids in ecosystems in Africa.

The levels of PFBS (<39.71 ng L^{-1}), PFBA (<36.79 ng L^{-1}), PFHxA (<57.19 ng L^{-1}) established in surface waters in Africa were lower than the established EQS LOAEL-NOAEL values of 1,100,000–640,000 ng L^{-1} , 1,600,000–660,000 ng L^{-1} , 440,000–210,000 ng L^{-1} , respectively

Table 2Occurrence of PFASs with EQSs in aquatic biota and sediments across Africa (surface water, ng L⁻¹; sediments, ng g⁻¹ dw; invertebrates, ng g⁻¹ ww; fish, ng g⁻¹ ww).

PFASs	Matrix	Concentration	Type of waterbody	Country	Authors
PFOA	Sediment	0.14–772	Multiple rivers ^a	South Africa	FGM
		1.4–99.1	Lake Victoria basin (rivers)	Kenya	Orata et al. (2011)
		0.05–0.99	uMvoti Estuary	South Africa	Fauconier et al. (2020)
		0.05–0.05	aMakikulu Estuary	South Africa	Fauconier et al. (2020)
		<1–24.1	Lake Victoria basin (lake)	Kenya	Orata et al. (2009)
		0.88–13.60	Nairobi river basin	Kenya	Chirikona et al. (2022)
	Invertebrates	0.9–4.6	various rivers	Nigeria	Ololade et al. (2018)
		0.64–3.57	uMvoti Estuary	South Africa	Fauconier et al. (2020)
		0.34–6.5	aMakikulu Estuary	South Africa	Fauconier et al. (2020)
		<0.5–3.8	Winam Gulf, Lake Victoria	Kenya	Francis et al. (2008)
		<LOD–0.074	Bizerte lagoon	Tunisia	Barhoumi et al. (2022)
		<0.07–1.5	Vaal river	South Africa	Groffen et al. (2018)
	Fish	<LOQ–0.42	Olifants river	South Africa	Verhaert et al. (2017)
		<0.01–0.04	Loskop Dam	South Africa	Bangma et al. (2017)
		<0.02–61*	Kalk Bay	South Africa	Ojemaye and Petrik (2019)
		0.12–1.01	uMvoti Estuary	South Africa	Fauconier et al. (2020)
		0.09–2.96	aMakikulu Estuary	South Africa	Fauconier et al. (2020)
		<2.53–121	Multiple rivers ^a	South Africa	FGM
		1.64–10.29	Southwest rivers	Nigeria	Ololade (2014)
		5.1–10.4	various rivers	Nigeria	Ololade et al. (2018)
		2.44–11.74	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<1–4.0	Lake Victoria basin (lake)	Kenya	Orata et al. (2011)
		0.47–0.91	uMvoti Estuary	South Africa	Fauconier et al. (2020)
		0.83–2.50	aMakikulu Estuary	South Africa	Fauconier et al. (2020)
PFOS	Sediment	<1–57.5	Lake Victoria basin (river)	Kenya	Orata et al. (2011)
		0.23–0.50	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.9–35.7	Winam Gulf, Lake Victoria	Kenya	Francis et al. (2008)
		0.025–0.661	Bizerte lagoon	Tunisia	Barhoumi et al. (2022)
		<LOD–0.866	Lake Kariba	Zambia	Simukoko et al. (2023)
		<0.12–460.7	Vaal river	South Africa	Groffen et al. (2018)
	EQSs	<0.025–0.77	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.066–0.15	Gulf of Guinea	Nigeria-Ghana	Ekperusi et al. (2023)
		0.32–1.65	Loskop Dam	South Africa	Bangma et al. (2017)
		0.18–28	uMvoti Estuary	South Africa	Fauconier et al. (2020)
		0.09–21.1	aMakikulu Estuary	South Africa	Fauconier et al. (2020)
		0.15–2.7	Olifants river	South Africa	Verhaert et al. (2017)
	Fish	<0.12–35.5	Vaal river	South Africa	Groffen et al. (2018)
		LOQ–0.58	uMvoti Estuary	South Africa	Fauconier et al. (2020)
		<LOQ–1.76	aMakikulu Estuary	South Africa	Fauconier et al. (2020)
		0.776–118	Various sites	South Africa	Christie et al. (2016)
		<LOD–0.47	Nairobi river basin	Kenya	Chirikona et al. (2022)
		0.575–2.26	Various sites	South Africa	Christie et al. (2016)
PFHxS	SW; Sediment	<0.21–0.4	Vaal river	South Africa	Groffen et al. (2018)
		<LOD–0.034	Bizerte lagoon	Tunisia	Barhoumi et al. (2022)
	Invertebrates	<0.21–1.8	Vaal river	South Africa	Groffen et al. (2018)
		<0.32–1.6	Vaal river	South Africa	Groffen et al. (2018)
	Fish	0.127–0.86	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		<0.05–0.021	Lake Tana	Ethiopia	Ahrens et al. (2016)
PFBA	Invertebrates	0.15–0.15	uMvoti Estuary	South Africa	Fauconier et al. (2020)
		0.15–0.15	aMakikulu Estuary	South Africa	Fauconier et al. (2020)
	Sediment	0.55–5.47	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<0.4–11.9	Vaal river	South Africa	Groffen et al. (2018)
	Fish	0.15–0.25	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.46–1.50	Nairobi river basin	Kenya	Chirikona et al. (2022)
PFHxA	Invertebrates	<0.54–0.9	Vaal river	South Africa	Groffen et al. (2018)
		<0.54–1.7	Vaal river	South Africa	Groffen et al. (2018)
	Fish	<LOQ	Atlantic Ocean	Nigeria	Ekperusi et al. (2023)
		<LOD–0.677	Lake Kariba	Zambia	Simukoko et al. (2023)
	Sediment	15.9–61*	Kalk Bay	South Africa	Ojemaye and Petrik (2019)
		<0.004–0.07	Loskop Dam	South Africa	Bangma et al. (2017)
PFNA	Invertebrates	<LOQ–0.14	Olifants river	South Africa	Verhaert et al. (2017)
		<0.025–0.28	Lake Tana	Ethiopia	Ahrens et al. (2016)
	Fish	0.053–1.05	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<LOQ–0.82	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
	Sediment	0.293–0.710	Various sites	South Africa	Christie et al. (2016)
		<LOQ	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
PFBS	Nile crocodiles	0.12–6.18	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<0.37–0.4	Vaal river	South Africa	Groffen et al. (2018)
	Sediment	<0.37–0.8	Vaal river	South Africa	Groffen et al. (2018)
		<0.025–0.5	Lake Tana	Ethiopia	Ahrens et al. (2016)
	Fish				

Mean ng g⁻¹ dw values reported; <LOQ = below limit of quantification; <LOD = below limit of detection; dw = dry weight; Multiple rivers^a = Olifants, Eerste, Diep, Plankenburg and Vaal Rivers; FGM=Fagbayigbo et al. (2018); Groffen et al. (2018); Mudumbi et al. (2014a,b); 67 ng L⁻¹ = Threshold to protect benthic organisms; 25 ng L⁻¹* = Threshold to protect pelagic organisms.

(Table 3). The other detected PFASs (PFUnDA, PFDA, PFUnDA, PFDoDA, PFTrDA, PFTeDA, PFPeS, PFHxS, PFDS, PFHpS, PFHpA, FOSA, FHxSA, MeFOSAA, EtFOSAA, FBSA, 6:2 FTSA, 4:2 FTS, 8:2 FTS, GenX, ADONA, PFONs, PFNs, PFOUDS, and PFONS) have no EQS, despite being prevalent in Africa.

Furthermore, according to the European Water Framework Directive (WFD) established in 2013, permitted annual average values for PFOS in surface water are much lower, at 0.13–0.65 ng L⁻¹, and the new proposal suggests a combined PFAS limit of 4.4 ng L⁻¹ (<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0540>). Considering these stricter thresholds, the observed levels in Africa may still exceed safe limits for certain regulatory frameworks. Additionally, for biota, the EU has established EQS for PFOS at 9.1 µg kg⁻¹ ww, which further highlights the potential for risk even at lower concentrations (Munné et al., 2023).

3.4. Bioaccumulation of PFASs in Africa

Contamination of aquatic systems is of concern since PFASs can bioaccumulate and bio-magnify within aquatic food webs (Bui et al., 2024), especially in tropical environments. While short-chain PFASs are mainly found in the water column, long-chain PFASs tend to bind to particles and bioaccumulate in the food chain (Ekperusi et al., 2023). Over nine studies have reported PFAS bioaccumulation in various African aquatic organisms, including species such as Nile perch and crocodiles, with levels of PFOS observed to have several orders of magnitude higher in predator tissues compared to lower trophic organisms, as shown in Fig. 2 (Groffen et al., 2021; Barhoumi et al., 2022; Adeogun et al., 2024; Fagbayigbo et al., 2018; Kasambala et al., 2024; Ekperusi et al., 2023; Arinaitwe et al., 2021; Faounier et al., 2023; Verhaert et al., 2017). Quantitative bioaccumulation factors (BAFs) for PFOS in fish from Africa range from 2 to 290 L kg⁻¹ ww, suggesting that top predators are particularly vulnerable to PFAS bioaccumulation (Koch et al., 2020). However, many of these studies have not specifically focused on bioaccumulation pathways and their ecological implications, underscoring the need for further research in this area.

A recent study by Adeogun et al. (2024) on two freshwater lakes in Nigeria (Asejire and Eleyele) demonstrated significant bioaccumulation of PFASs across multiple trophic levels, with species such as *Clarias gariepinus* and *Oreochromis niloticus* showing elevated levels of PFOS, PFDA, and EtFOSE in muscle tissues. The study highlights the influence of urbanization on PFAS load, with urban lakes like Eleyele displaying higher biomagnification factors (BMFs) for these compounds compared to suburban lakes. The estimated BMFs for PFOS and EtFOSE exceeded 1, indicating significant magnification along the food chain, particularly in higher trophic organisms such as pelagic and benthic omnivores. These findings underscore the ecological risks posed by PFAS bioaccumulation, especially in urbanised regions where anthropogenic activities increase contaminant load (Adeogun et al., 2024). Furthermore, this study adds valuable insight into the potential health risks for human populations that rely on these species for food, as the biomagnification of PFASs in fish may lead to increased dietary exposure.

Globally, PFASs like PFOS and PFOA have been reported to bio-magnify through food chains, with studies in North America and Europe showing biomagnification factors (BMFs) of up to 12.5 in fish-eating birds (Newsted et al., 2017). Comparable trends are emerging in ecosystems in Africa, especially in apex predators like crocodiles. The bioaccumulation of PFASs presents a significant ecological threat, but it also has direct human health implications, particularly for communities that depend on fish as a primary source of protein (Rickard et al., 2022).

3.5. Ecological risks of PFASs in Africa

As noted earlier, PFAS levels in Africa are generally lower than in industrialized countries, but certain areas have concentrations that exceed ecological quality standards, presenting potential risks to aquatic

life (Groffen et al., 2021). However, to the best of our knowledge, only one study by Ekperusi et al. (2023) has assessed the potential risks associated with PFAS exposure to aquatic organisms from the Gulf of Guinea. The authors reported estimated daily intakes of 0.26 and 0.0014 ng kg⁻¹ day⁻¹, for fish and shrimps, respectively, resulting in hazard ratio values less than the safety threshold (1.00) for both fish (0.40) and shrimp (0.0023) (Ekperusi et al., 2023).

To bridge the gap regarding the paucity of literature about the ecological risks posed by PFASs, we have calculated the theoretical ecological risks posed by PFASs based on the reported environmental data (Table 1–3, S2). We used the risk quotients (RQs) calculated as per Equation (1) (Ngeno et al., 2023).

$$RQ = \left(\frac{MEC}{PNEC} \right) \quad \text{Equation (1)}$$

where MEC is the maximum environmental concentration of a PFAS reported and PNEC is the Predicted No Effect Concentration.

In this review, the MEC values were obtained from peak PFAS levels reported in surface waters and effluents. Surface water matrices are utilised because all studies included in the review reported PFAS concentrations in this matrix, while effluents are included due to their direct discharge into aquatic systems. In addition, a PNEC (<25000) has been reported for PFOS by the Norwegian Pollution Control Authority (NPCA) in freshwater (Groffen et al., 2021). Further to this, PNEC values (for PFOS and PFOA) in the NPCA range in both freshwater and marine water have been referenced for EQs in WWTWs (Table 4) (Mhadhbi et al., 2012). Therefore, only PFOS was considered for computation and comparison purposes. The PNEC values of PFOS and PFOA in freshwater and marine waters are 5100 and 1100 ng L⁻¹, and 2.2×10^6 and 1.19×10^5 ng L⁻¹, respectively (Mhadhbi et al., 2012). An RQ value > 1 indicates potential high risk, and $0.1 < RQ < 1$ and $RQ < 0.1$ represent potential medium and low risks, respectively (Ngeno et al., 2023).

Based on the model computations (Tables 4 and 5), marine species in Africa had higher RQs approaching 1 and, generally, faced a greater risk due to exposure to PFASs compared to freshwater species. The high alkalinity of marine environments may not provide favourable conditions for PFAS biodegradation. The average range of RQs in effluent discharge is 0.1 ± 0.23 , suggesting a low to medium risk (Mhadhbi et al., 2012). The average RQs for PFOS in aquatic ecosystems is 0.1 with a standard deviation of ± 0.04 , indicating a low risk of PFASs in the aquatic systems of Africa. However, due to the high bioaccumulation factors of PFASs, there are concerns regarding the potential for high-risk health hazards if mitigation measures are not promptly implemented (Verhaert et al., 2017).

3.6. Future research directions and perspectives on the management of PFASs

Strengthening regulatory frameworks: Many African countries endorsed the Stockholm Convention in 2004 to monitor POPs, resulting in the development of various National Implementation Plans (NIPs) (Bouwman, 2004). PFASs (PFOSF, PFOS, and their salts) were added to Annex B in 2009 and, PFOA and PFHxS to Annex A in 2019 (Stockholm Convention, 2019). Since 2009, most African countries have not updated their NIPs to include these updates (Ssebugere et al., 2020). The general absence or weak regulatory frameworks for the management of PFASs in Africa hinders progress towards their monitoring in the environment (Ssebugere et al., 2020). There is an urgent need to strengthen the regulatory frameworks in Africa and emphasise proactive measures such as prevention, reduction, and safe disposal practices concerning PFASs.

Prioritising funding for environmental monitoring and protection: PFAS contamination in sub-Saharan Africa is likely to rise in tandem with urban development. This trend necessitates improved monitoring, identification of contamination hotspots, and evaluation of associated

Table 3Levels of PFASs without EQS in aquatic systems across Africa (surface water, ng L⁻¹; sediments, ng g⁻¹ dw; invertebrates, ng g⁻¹ ww; and fish, ng g⁻¹ ww).

PFASs	Matrix	Concentration	Aquatic ecosystem	Country	Authors
PFBS	Surface water	<LOQ-24.7	Multiple rivers*a	South Africa	FGM
		0.01–1.0	Nairobi river basin	Kenya	Chirikona et al. (2022)
		0.7–1.7	Nakivubo wetland	Uganda	Dalahmeh et al. (2020)
		0.05–0.2	River Kagera & Sio	Uganda	Arinaitwe et al. (2021)
		0.02–0.11	Open Lake (Victoria)	Uganda	Arinaitwe et al. (2021)
		<LOD-2.3	Lake Victoria	Uganda	Dalahmeh et al. (2020)
		8.54–39.71	Hartbeespoort/Roodeplaat dam	South Africa	Batayi et al. (2021)
	Sediment	<LOQ	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		0.12–6.18	Nairobi river basin	Kenya	Chirikona et al. (2022)
	Invertebrates (ng/g)	<0.37–0.4	Vaal river	South Africa	Groffen et al. (2018)
	Fish	<0.37–0.8	Vaal river	South Africa	Groffen et al. (2018)
		<0.025–0.5	Lake Tana	Ethiopia	Ahrens et al. (2016)
PFHpA	Surface water	<LOD-0.9	Nakivubo wetland	Uganda	Dalahmeh et al. (2020)
		10.5–77.6	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		0.4–1.0	River Sosiani	Kenya	Shafique et al. (2016)
		0.13–2.41	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<LOQ-2.5	Vaal River	South Africa	Groffen et al. (2018)
		<LOD	Pra and Kakum river	Ghana	Essumang et al. (2017)
		<0.21–2.0	River Kagera & Sio	Uganda	Arinaitwe et al. (2021)
		<LOD-0.89	Open Lake (Victoria)	Uganda	Arinaitwe et al. (2021)
		7.59–74.22	Hartbeespoort/Roodeplaat dam	South Africa	Batayi et al. (2021)
		<LOD	Lake Victoria	Uganda	Dalahmeh et al. (2020)
	Sediment	0.105–0.81	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		<0.01–0.017	Lake Tana	Ethiopia	Ahrens et al. (2016)
	Fish*	<LOD–0.017	Bizerte lagoon	Tunisia	Barhoumi et al. (2022)
PFDA	Surface water	<0.05–0.12	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.6–0.7	Nakivubo wetland	Uganda	Dalahmeh et al. (2020)
		BDL-0.06	Pra and Kakum river	Ghana	Essumang et al. (2017)
		0.04–0.67	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<LOD-1.18	Lake Kariba	Zambia	Simukoko et al. (2023)
		0.21–0.91	River Kagera & Sio	Uganda	Arinaitwe et al. (2021)
		0.27–0.59	Open Lake (Victoria)	Uganda	Arinaitwe et al. (2021)
		10.8–21.6	River Sosiani	Kenya	Shafique et al. (2016)
		<LOQ-32.0	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		<LOD	Lake Victoria	Uganda	Dalahmeh et al. (2020)
	Sediment	<LOQ-0.18	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		0.47–3.76	Nairobi river basin	Kenya	Chirikona et al. (2022)
	Fish	<0.01–0.023	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.47–3.76	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<0.71–8.7	Vaal river	South Africa	Groffen et al. (2018)
		20.1–159*	Kalk Bay	South Africa	Ojemaye and Petrik (2019)
		0.016–0.053	Atlantic Ocean	Gulf of Guinea	Ekperusi et al. (2023)
		<0.01–0.213	Loskop Dam	South Africa	Bangma et al. (2017)
		<LOQ-2.34	uMvoti-aMakikulu	South Africa	Fauconier et al. (2020)
		0.32–0.93	Lake Tana	Ethiopia	Ahrens et al. (2016)
		<0.71–1.8	Vaal river	South Africa	Groffen et al. (2018)
		<0.85–1.73	uMvoti-aMakikulu	South Africa	Fauconier et al. (2020)
PFUnDA	Nile crocodiles (ng/g)	0.118–6.13	Various sites	South Africa	Christie et al. (2016)
	Surface water	<0.05–0.078	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.2 ± 0.3	Nakivubo wetland	Uganda	Dalahmeh et al. (2020)
		<LOQ-32.0	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		<0.09–1.29	River Kagera & Sio	Uganda	Arinaitwe et al. (2021)
		0.05–13.22	Nairobi river basin	Kenya	Chirikona et al. (2022)
		0.17–0.42	Open Lake (Victoria)	Uganda	Arinaitwe et al. (2021)
		10.5–15.9	River Sosiani	Kenya	Shafique et al. (2016)
		<LOD-2.3	Lake Victoria	Uganda	Dalahmeh et al. (2020)
		0.092–0.845	Various sites	South Africa	Christie et al. (2016)
		<0.95–4.7	Vaal river	South Africa	Groffen et al. (2018)
	Fish	0.027–0.061	Atlantic Ocean	Gulf of Guinea	Ekperusi et al. (2023)
		<0.02*	Kalk Bay	South Africa	Ojemaye and Petrik (2019)
		<0.005–0.41	Lake Tana	Ethiopia	Ahrens et al. (2016)
		<0.95–2.0	Vaal river	South Africa	Groffen et al. (2018)
PFDoDA	Invertebrates (ng/g)	<LOQ-0.147	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		0.33–1.65	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<0.01–0.029	Lake Tana	Ethiopia	Ahrens et al. (2016)
	Sediment	<LOQ	Plankenburg river	South Africa	Fagbayigbo et al. (2018)
		0.05–0.1	River Kagera	Uganda	Arinaitwe et al. (2021)
		0.03–0.08	River Sio	Uganda	Arinaitwe et al. (2021)
		0.03–2.40	Nairobi river basin	Kenya	Chirikona et al. (2022)
		0.03–0.07	Open Lake (Victoria)	Uganda	Arinaitwe et al. (2021)
		23.3–31.6	River Sosiani	Kenya	Shafique et al. (2016)
	Invertebrates	<0.07–0.3	Vaal river	South Africa	Groffen et al. (2018)
		<LOQ-1.30	uMvoti- aMakikulu	South Africa	Fauconier et al. (2020)
	Sediment	<LOQ	Plankenburg river	South Africa	Fagbayigbo et al. (2018)

(continued on next page)

Table 3 (continued)

PFASs	Matrix	Concentration	Aquatic ecosystem	Country	Authors
PFTrDA	Nile crocodiles (ng/g)	<0.01–0.019	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.30–1.35	Nairobi river basin	Kenya	Chirikona et al. (2022)
		0.03–0.63	uMvoti-aMakikulu	South Africa	Fauconier et al. (2020)
		0.0151–0.92	Various sites	South Africa	Christie et al. (2016)
		<0.07–1.9	Vaal river	South Africa	Groffen et al. (2018)
		<0.16–1.37	uMvoti-aMakikulu	South Africa	Fauconier et al. (2020)
		0.014–0.078	Loskop Dam	South Africa	Bangma et al. (2017)
		0.017–0.036	Atlantic Ocean	Gulf of Guinea	Ekperusi et al. (2023)
		<0.02*	Kalk Bay	South Africa	Ojemaye and Petrik (2019)
		<0.01–0.51	Lake Tana	Ethiopia	Ahrens et al. (2016)
	Fish	<0.07–0.2	Vaal river	South Africa	Groffen et al. (2018)
		<LOQ–0.06	uMvoti-aMakikulu	South Africa	Fauconier et al. (2020)
		<0.07–0.8	Vaal river	South Africa	Groffen et al. (2018)
		0.066–0.124	Atlantic Ocean	Gulf of Guinea	Ekperusi et al. (2023)
		<LOQ–0.33	uMvoti-aMakikulu	South Africa	Fauconier et al. (2020)
PFTeDA	Sediment	<0.01–0.017	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.21–1.01	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<0.04–1.04	River Kagera & Sio	Uganda	Arinaitwe et al. (2021)
	Surface water	<LOD–0.02	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<0.10–0.2	Vaal river	South Africa	Groffen et al. (2018)
	Fish	<LOQ	Atlantic Ocean	Guinea gulf	Ekperusi et al. (2023)
		<0.01	Lake Tana	Ethiopia	Ahrens et al. (2016)
		<0.012–0.026	Lake Tana	Ethiopia	Ahrens et al. (2016)
		0.10–0.75	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<LOD–0.54	Nairobi river basin	Kenya	Chirikona et al. (2022)
PFDS	Invertebrates (ng/g)	<0.01–0.03	Vaal river	South Africa	Groffen et al. (2018)
	Fish	<0.01–0.1	Vaal river	South Africa	Groffen et al. (2018)
	Surface water	0.01–1.30	Nairobi river basin	Kenya	Chirikona et al. (2022)
	Sediment	1.55	Nairobi river basin	Kenya	Chirikona et al. (2022)
FOSA	Surface water	<LOD–0.01	River Kagera & Sio	Uganda	Arinaitwe et al. (2021)
					Chirikona et al. (2022)
EtFOSAA	Surface water	<LOD–0.01	Open Lake (Victoria)	Kenya	Chirikona et al. (2022)
		0.01–0.6	Nairobi river basin	Kenya	Chirikona et al. (2022)
		<LOD–0.4	Nakivubo wetland	Uganda	Dalahmeh et al. (2020)
	Sediment	<LOD–0.24	Lake Victoria	Uganda	Arinaitwe et al. (2021)
PFAS*	Surface water	0.44–1.51	Nairobi river basin	Kenya	Chirikona et al. (2022)
PFAS*	Surface water	<0.002–30.11	Nairobi river basin	Kenya	Chirikona et al. (2022)
	Sediment	<LOD–1.62	Nairobi river basin	Kenya	Chirikona et al. (2022)

PFAS* = FBFA, 6:2FTSA, 4:2 FTS, 8:2 FTS, FHxSA, GenX, ADONA, PFONs, PFN, PFOUDS, PFONS, FHxSA, MeFOSAA, PFHxS, PFNS, PFPeS, PFHpS, PFHpA; Fish* = ng g⁻¹ dw.

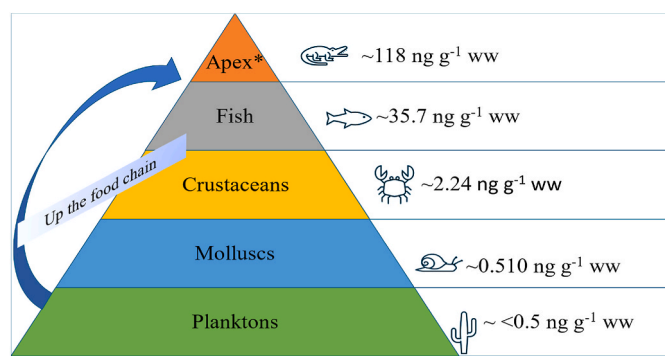


Fig. 2. PFAS levels in matrices across the trophic chain in African aquatic ecosystem.

*Apex predators include crocodiles and Nile Perch.

risks across the continent (Ripanda et al., 2021). However, this review found limited studies on the ecological impacts of emerging contaminants like PFASs. Additionally, the current literature shows that the existing research primarily focuses on legacy PFASs, neglecting the new and potentially more hazardous compounds (Ssebugere et al., 2020). The current data gaps make it challenging to fully understand the broader effects of emerging PFASs on ecosystems and human health. The lack of studies from certain regions, particularly in Central and North Africa, limited our ability to assess the true extent of PFAS contamination across

the continent and to make meaningful comparisons between regions and ecosystems. As a result, our understanding of PFAS contamination remains fragmented, and further studies are needed to fill these geographical gaps to provide a more comprehensive assessment of PFAS pollution in Africa.

Our findings suggest the need for African countries invest more in research and development efforts and prioritize environmental monitoring and protection. Unfortunately, many countries in Africa allocate only about 1% of their GDP to research and development, with some countries allocating even less (Groffen et al., 2021). The resources available for research and development; for instance, acquiring analytical equipment capable of analysing PFASs in various environmental matrices are inadequate. The limited resources in some countries also imply that it is increasingly difficult for many African countries to invest in advanced treatment technologies for the efficient removal of PFASs from wastewater effluent (UNEP, 2017). By supporting research and monitoring, African countries can proactively address these knowledge gaps, fostering better environmental management and supporting global efforts to address environmental pollution.

Establishing factors influencing PFAS distributions: There is paucity of data about the monitoring and management of PFASs in most countries in Africa, making it challenging to understand the risk posed to both humans and the ecosystems (O'Connor et al., 2022). For instance, the social factors influencing PFAS occurrence in the environment have not yet been studied in Africa. Addressing improper waste disposal practices and various socioeconomic factors that impact waste disposal is critical for the effective management of PFASs (Zhuo et al., 2023). By

Table 4
Estimated risks of PFOS and PFOA in effluents from WWTWs across Africa.

Location	MEC (ng L ⁻¹)	PFOS		MEC (ng L ⁻¹)	PFOA		References
		RQs			RQs		
		Freshwater	Marine		Freshwater	Marine	
Nigeria	382.4	0.07498	0.347636	416.3	0.000189	0.003498	Sindikú et al.
Kenya	673	0.131961	0.611818	286	0.00013	0.002403	Chirikona et al. (2015)
Uganda	3.1	0.000608	0.002818	2.4	1.09×10^{-6}	2.02×10^{-5}	Dalahmeh et al. (2020)
South Africa	94.9	0.018608	0.086273	13.1	5.95×10^{-6}	0.00011	Adeleye (2016)
South Africa	126	0.018608	0.114545	8.7	3.95×10^{-6}	7.31×10^{-5}	Kibambe et al. (2020)
South Africa	10.24	0.002008	0.009309	37.7	1.71×10^{-5}	0.000317	Morethe et al. (2024)

Table 5
Theoretical PFASs risks quotients due to PFOA in aquatic ecosystems across Africa.

Habitat	MEC (ng L ⁻¹)	Theoretical RQs	Authors
Multiple rivers, South Africa	346.33	6.7908 × 10 ⁻²	Batayi et al. (2021); Fagbayigbo et al. (2018); Groffen et al. (2018); Mudumbi et al. (2014a, b); Verhaert et al. (2017) Hope (2020) ^a
Indian Ocean, Mozambique	0.1409	1.28 × 10 ⁻⁴	Simukoko et al. (2023)
Lake Kariba, Zambia	0.866	1.7 × 10 ⁻⁴	
Lake Victoria, Uganda	13.23	2.594 × 10 ⁻³	Arinaitwe et al. (2021); Dalahmeh et al., 2020; Orata et al. (2009)
Multiple rivers, Uganda	0.12	2.35 × 10 ⁻⁵	Arinaitwe et al. (2021)
Nairobi river, Kenya	1.37	2.69 × 10 ⁻⁴	Chirikona et al. (2022)
Lake Tana, Ethiopia	0.22	4.31 × 10 ⁻⁴	Ahrens et al. (2016)
Niger river, Mali	4.7	9.22 × 10 ⁻⁴	UNEP (2017)

^a A PNEC value of 1100 ng L⁻¹ for marine waters was used in the calculation.

recognizing and addressing these multifaceted issues, the scientific and regulatory communities need to coordinate and address the environmental risks posed by pollutants such as PFASs.

Conducting detailed environmental risk assessments with respect to PFASs: The review found that the ecological impacts of PFASs on aquatic organisms have only been assessed in the Gulf of Guinea (Ekperusi et al., 2023). Expanding PFAS ecological risk assessments across Africa is essential, given the continent’s diverse range of aquatic systems, which include both marine and freshwater environments. Additionally, while existing studies primarily focus on legacy pollutants, recent assessments suggest that PFASs may exhibit higher RQs and PNECs compared to other POPs globally. Wang et al. (2024) have reported that PNECs of PFAS are often higher than those of other POPs, highlighting the significant ecological risks posed by PFASs, particularly to freshwater ecosystems. These ecosystems are not only rich in biodiversity but also play a crucial role in providing food resources to local communities, directly influencing human health and livelihoods (Barhoumi et al., 2022). Additionally, the unique ecological characteristics of these ecosystems suggest that the effects of PFASs could vary significantly across regions. As industrialization and urbanization increase, the risk of PFAS contamination in these environments increases, making it essential to assess these risks and implement protective measures to mitigate their impact. Expanding the scope of PFAS risk assessments will help better understand the extent and severity of contamination, guiding policymakers in developing effective strategies to address this.

The risk quotients calculated in this study are based on available MECs and PNECs. However, the reliance on theoretical calculations highlights a gap in empirical data, particularly in African contexts where long-term PFAS monitoring is scarce. This study, therefore, highlights the need for future studies to generate empirical data across different

ecosystems in Africa to validate these risk assessments. Regular monitoring would provide a more robust basis for calculating risk quotients and enhance the reliability of PFAS risk assessments in African aquatic environments. Furthermore, the safe levels (MECs and PNECs) used in this review were based on ecosystems from Europe. Given the unique environmental conditions in Africa, future research needs to focus on collecting empirical data across various ecosystems in Africa to validate these risk assessments and/or develop MECs and PNECs specific to Africa.

Although the primary focus of this study is on the ecological risks posed by PFAS to aquatic organisms, it is important to recognize that human populations living near contaminated water sources might also be indirectly exposed to these contaminants. Communities relying on these water sources may face health risks, particularly through the consumption of contaminated fish or water, as PFASs can bioaccumulate with continued consumption (Adewuyi and Li, 2024). Global human toxicity studies have shown adverse effects of PFAS bioaccumulation in humans. These effects include endocrine disruption, reproductive disorders such as miscarriages, kidney diseases, liver damage, genotoxicity and carcinogenicity (Rickard et al., 2022; Spyrou et al., 2024; Ssebugere et al., 2020). Therefore, while our study emphasizes non-human biota, there is a potential extrapolation of risk to nearby human populations, especially those relying on aquatic resources.

Increasing public awareness of PFASs and their effects: The key findings suggest urbanisation is increasing PFASs exposure implying a need for their assessment in water bodies and treatment plants located in urban areas. Therefore, a need to encourage proper waste disposal practices, considering the widespread presence of PFASs in everyday consumer products. Research should encourage public awareness campaigns to address the potential environmental impact of improper disposal on PFAS contamination (Shehu et al., 2022). Furthermore, there should be advocacy for the establishment of PFASs EQS standards and regulations specific to WWTWs in Africa, where currently no uniform guidelines exist. This can be done in collaboration with international organizations and regulatory bodies to develop comprehensive standards to preserve aquatic ecosystems in Africa. This proactive approach can contribute to the formulation of effective regulatory frameworks tailored to the unique challenges faced by African nations in managing PFAS pollution in WWTWs.

4. Conclusions

The reviewed literature reported widespread occurrence of over 35 PFASs congeners in aquatic ecosystems and wastewater treatment matrices across 11 African countries. PFASs levels exhibit considerable variability, ranging from <2.0 to 772 ng L⁻¹ in aquatic system matrices and 2.35–832 ng L⁻¹ in wastewater. Among the detected PFASs, PFOA, PFOS, PFNA, and PFDA are prominently observed in aquatic environments, indicating a higher prevalence of PFCAs than PFSAs. Notably, PFOA and PFHxS emerge as the dominant compounds in wastewater treatment works (WWTWs), contrasting with global trends where PFOS typically dominates. River sediments exhibit exceptionally high levels reaching 772 ng g⁻¹ dw for PFOA, while PFHxS peaks at 832 ng L⁻¹ in

wastewater effluents during dry seasons. Wastewater treatment plants are identified as significant sources of PFASs in aquatic ecosystems. Urbanization, seasonal variations, treatment processes, and industrial activities also collectively contribute to PFASs exposure in aquatic environments. The literature also indicates that PFAS levels are increasing in recent times, correlating with increasing levels of industrialization. WWTWs have been found to have higher PFASs loads than aquatic systems, highlighting their role as significant contributors to PFASs pollution. Furthermore, biomagnification of PFASs in organisms that are high in the food chain poses significant ecological concerns.

CRedit authorship contribution statement

Ashirafu Miiro: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Oghenekaro Nelson Odume:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **George William Nyakairu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Silver Odongo:** Writing – review & editing. **Henry Matovu:** Writing – review & editing, Methodology. **Charles Drago Kato:** Writing – review & editing, Conceptualization. **Ivan Španik:** Writing – review & editing, Conceptualization. **Mika Sillanpää:** Writing – review & editing, Conceptualization. **Edward Mubiru:** Writing – review & editing, Conceptualization. **Patrick Ssebugere:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.chemosphere.2024.143590>.

Data availability

No data was used for the research described in the article.

References

- Adeleye, A.P., 2016. Perfluorinated compounds, bisphenol A, and acetaminophen in selected wastewater treatment plants in and around Cape town, South Africa. Doctoral Dissertation, Cape Peninsula University of Technology. (Accessed 14 October 2024).
- Adeogun, A.O., Chukwuka, A.V., Ibor, O.R., Asimakopoulou, A.G., Zhang, J., Arukwe, A., 2024. Occurrence, bioaccumulation and trophic dynamics of per-and polyfluoroalkyl substances in two tropical freshwater lakes. *Environ. Pollut.* 346, 123575. <https://doi.org/10.1016/j.envpol.2024.123575>.
- Adewuyi, A., Li, Q., 2024. Per-and polyfluoroalkyl substances contamination of drinking water sources in Africa: pollution sources and possible treatment methods. *Chemosphere* 365, 143368. <https://doi.org/10.1016/j.chemosphere.2024.143368>.
- Ahrens, L., Bundschuh, M., 2014. Fate and effects of poly- and perfluoroalkyl substances in the aquatic environment: a review. *Environ. Toxicol. Chem.* 33, 1921–1929. <https://doi.org/10.1002/etc.2663>.
- Ahrens, L., Gashaw, H., Sjöholm, M., Gebrehiwot, S.G., Getahun, A., Derbe, E., et al., 2016. Poly- and perfluoroalkylated substances (PFASs) in water, sediment and fish muscle tissue from Lake Tana, Ethiopia and implications for human exposure. *Chemosphere* 165, 352–357. <https://doi.org/10.1016/j.chemosphere.2016.09.007>.
- Arinaitwe, K., Keltch, N., Taabu-Munyaho, A., Reemtsma, T., Berger, U., 2021. Perfluoroalkyl substances (PFASs) in the Ugandan waters of Lake Victoria: spatial distribution, catchment release, and public exposure risk via municipal water consumption. *Sci. Total Environ.* 783, 1–9. <https://doi.org/10.1016/j.scitotenv.2021.146970>.
- Ankley, G.T., Cureton, P., Hoke, R.A., Houde, M., Kumar, A., Kurias, J., et al., 2021. Assessing the ecological risks of per- and polyfluoroalkyl substances: current state-of-the-science and a proposed path forward. *Environ. Toxicol. Chem.* 40 (3), 564–605. <https://doi.org/10.1002/etc.4869>.
- Baguma, G., Bamanya, G., Gonzaga, A., Ampaire, W., Onen, P., 2023. A systematic review of contaminants of concern in Uganda: occurrence, sources, potential risks, and removal strategies. *Pollutants* 3 (4), 544–586. <https://doi.org/10.3390/pollutants3040037>.
- Bangma, J.T., Reiner, J.L., Botha, H., Cantu, T.M., Gouws, M.A., Guillet, M.P., Koelmel, J.P., Luus-Powell, W.J., Myburgh, J., Rynders, O., Sara, J.R., Smit, W.J., Bowden, J.A., 2017. Tissue distribution of perfluoroalkyl acids and health status in wild Mozambique tilapia (*Oreochromis mossambicus*) from Loskop Dam, Mpumalanga, South Africa. *J. Environ. Sci.* 61, 59–67. <https://doi.org/10.1016/j.jes.2017.03.041>.
- Barhoumi, B., Sander, S.G., Driss, M.R., Tolosa, I., 2022. Survey of legacy and emerging per- and polyfluorinated alky substances in Mediterranean seafood from a North African ecosystem. *Environ. Pollut.* 292, 118398. <https://doi.org/10.1016/j.envpol.2021.118398>.
- Batayi, B., Okonko, O.J., Daso, A.P., 2021. Poly-and perfluorinated substances in environmental water from the Hartbeespoort and Rooiblaats Dams, South Africa. *WaterSA* 47 (1), 54–66. <https://doi.org/10.17159/wsa/2021.v47.i1.9445>.
- Buck, R.C., Korzeniowski, S.H., Laganis, E., Adamsky, F., 2021. Identification and classification of commercially relevant per- and poly-fluoroalkyl substances (PFAS). *Integrated Environ. Assess. Manag.* 17 (5), 1045–1055. <https://doi.org/10.1002/ieam.4450>.
- Bui, T.H., Zuverza-Mena, N., Dimkpa, C.O., Nason, S.L., Thomas, S., White, J.C., 2024. PFAS remediation in soil: an evaluation of carbon-based materials for contaminant sequestration. *Environ. Pollut.* 344, 123335. <https://doi.org/10.1016/j.envpol.2024.123335>.
- Bouwman, H., 2004. South Africa and the Stockholm Convention on persistent organic pollutants: science policy. *South Afr. J. Sci.* 100 (7), 323–328. <https://hdl.handle.net/10520/EJC96286>.
- Chirikona, F., Filipovic, M., Ooko, S., Orata, F., 2015. Perfluoroalkyl acids in selected waste-water treatment plants and their discharge load within the Lake Victoria basin in Kenya. *Environ. Monit. Assess.* 187 (5), 238. <https://doi.org/10.1007/s10661-015-4425-6>.
- Chirikona, F., Quinete, N., Gonzalez, J., Mutua, G., Kimosop, S., Orata, F., 2022. Occurrence and distribution of per- and polyfluoroalkyl substances from multi-industry sources to water, sediments and plants along Nairobi River basin, Kenya. *Int. J. Environ. Res. Publ. Health* 19 (15), 8980. <https://doi.org/10.3390/ijerph19158980>.
- Christie, I., Reiner, J.L., Bowden, J.A., Botha, H., Cantu, T.M., Govender, D., Guillet, M.P., Lowers, R.H., Luus-Powell, W.J., Pienaar, D., Smit, W.J., Guillet, L.J., 2016. Perfluorinated alky acids in the plasma of South African crocodiles (*Crocodylus niloticus*). *Chemosphere* 154, 72–78. <https://doi.org/10.1016/j.chemosphere.2016.03.072>.
- Connor, R., 2015. The United Nations World Water Development Report 2015: *Water for a Sustainable World*, vol. 1. The United Nations world water development report 2015: water for a sustainable world; 2015, pp. 55–67. (Accessed 10 April 2024).
- Dalahmeh, S., Björnberg, E., Elenström, A.K., Niwagaba, C.B., Komakech, A.J., 2020. Pharmaceutical pollution of water resources in Nakivubo wetlands and Lake Victoria, Kampala, Uganda. *Sci. Total Environ.* 710, 1–8. <https://doi.org/10.1016/j.scitotenv.2019.136347>.
- Divine, C., Zoderow, J., Frenchmeyer, M., Dally, K., Osborn, E., Anderson, P., 2020. Approach for Assessing PFAS Risk to Threatened and Endangered Species (Project ER18-1653). Department of Defense Strategic Environmental Research and Development Program (SERDP). <https://serdp-estcp.mil/projects>. (Accessed 15 March 2024).
- Ekperusi, A.O., Bely, N., Pollono, C., Mahé, K., Munschy, C., Aminot, Y., 2023. Prevalence of per- and polyfluoroalkyl substances (PFASs) in marine seafood from the Gulf of Guinea. *Chemosphere* 335, 139110. <https://doi.org/10.1016/j.chemosphere.2023.139110>.
- Elnakar, H., Ismail, U.M., Khan, M.F., Alnaimat, S., 2024. Tackling the dust-microplastic nexus: a review of sources, fate, and detection. *J. Hazard. Mater. Adv.* 14, 100418. <https://doi.org/10.1016/j.hazadv.2024.100418>.
- Essumang, D.K., Eshun, A., Hogarh, J.N., Bentum, J.K., Adjei, J.K., Negishi, J., Nakamichi, S., Habibullah-Al-Mamun, M., Masunaga, S., 2017. Perfluoroalkyl acids (PFAAs) in the Pra and Kakum River basins and associated tap water in Ghana. *Sci. Total Environ.* 579, 729–735. <https://doi.org/10.1016/j.scitotenv.2016.11.035>.
- Evich, M.G., Davis, M.J.B., McCord, J.P., Acrey, B., Awkerman, J.A., Knappe, D.R.U., Lindstrom, A.B., Speth, T.F., Tebes-Stevens, C., Strynar, M.J., Wang, Z., Weber, E.J., Henderson, W.M., Washington, J.W., 2022. Per- and polyfluoroalkyl substances in the environment. *Science* 375, 6580. <https://doi.org/10.1126/science.abg9065>.

- Fagbayigbo, B., Opeolu, B., Fatoki, O., Olatunji, O., 2018. Validation and determination of nine PFCS in surface water and sediment samples using UPLC-QTOF-MS. *Environ. Monit. Assess.* 190, 346. <https://doi.org/10.1007/s10661-018-6715-2>.
- Faucouner, G., Groffen, T., Wepener, V., Bervoets, L., 2020. Perfluorinated compounds in the aquatic food chains of two subtropical estuaries. *Sci. Total Environ.* 719, 135047. <https://doi.org/10.1016/j.scitotenv.2019.135047>.
- Francis, O., Natalia, Q., Anka, M., Friedrich, W., Rolf-Dieter, W., 2008. Perfluorooctanoic acid and perfluorooctane sulfonate in Nile Perch and tilapia from gulf of Lake Victoria. *Afr. J. Pure Appl. Chem.* 2, 75–79.
- Glüge, J., Scheringer, M., Cousins, I.T., Dewitt, J.C., Goldenman, G., Herzke, D., Lohmann, R., Ng, C.A., Trier, X., Wang, Z., 2020. An overview of the uses of per- and polyfluoroalkyl substances (PFASs). *Environ. Sci.: Process. Impacts* 22 (12), 2345–2373. <https://doi.org/10.1039/D0EM00291G>.
- Groffen, T., Wepener, V., Malherbe, W., Bervoets, L., 2018. Distribution of perfluorinated compounds (PFASs) in the aquatic environment of the industrially polluted Vaal River, South Africa. *Sci. Total Environ.* 627, 1334–1344. <https://doi.org/10.1016/j.scitotenv.2018.02.023>.
- Groffen, T., Nkuba, B., Wepener, V., Bervoets, L., 2021. Risks posed by per- and polyfluoroalkyl substances (PFAS) on the African continent, emphasizing aquatic ecosystems. *Integrated Environ. Assess. Manag.* 17 (4), 726–732. <https://doi.org/10.1002/ieam.4404>.
- Haimbaugh, A., Wu, C.C., Akemann, C., Meyer, D.N., Connell, M., Abdi, M., et al., 2022. Multi-and transgenerational effects of developmental exposure to environmental levels of PFAS and PFAS mixture in zebrafish (*Danio rerio*). *Toxics* 10 (6), 334. <https://doi.org/10.3390/toxics10060334>.
- Hamid, H., Li, L.Y., Grace, J.R., 2018. Review of the fate and transformation of per- and polyfluoroalkyl substances (PFASs) in landfills. *Environ. Pollut.* 235, 74–84. <https://doi.org/10.1016/j.envpol.2017.12.030>.
- Hope, K., 2020. Occurrence of major perfluoroalkyl substances (PFAS) in water samples from a transect of the Indian Ocean along the East African coast. Master's Dissertation, Örebro University. (Accessed 19 October 2024).
- Huang, C., Wu, L.-H., Liu, G.-Q., Shi, L., Guo, Y., 2018. Occurrence and ecological risk assessment of eight endocrine-disrupting chemicals in urban river water and sediments of South China. *Arch. Environ. Contam. Toxicol.* 75 (2), 224–235. <https://doi.org/10.1007/s00244-018-0527-9>.
- Ismail, U.M., Elnakar, H., Khan, M.F., 2023. Sources, fate, and detection of dust-associated perfluoroalkyl and polyfluoroalkyl substances (PFAS): a review. *Toxics* 11 (4), 335. <https://doi.org/10.3390/toxics11040335>.
- Jin, Y.H., 2006. An investigation of the PFOS and PFOA pollution in Three Gorges Reservoir are-as of the Yangtze River and surface water of Wuhan areas. *Ecol. Environ.* 15, 486–489. <https://doi.org/10.16258/j.cnki.1674-5906.2006.03.008>.
- Jin, Y.H., Liu, W., Sato, I., Nakayama, S.F., Sasaki, K., Saito, N., Tsuda, S., 2009. PFOS and PFOA in environmental and tap water in China. *Chemosphere* 77 (5), 605–611. <https://doi.org/10.1016/j.chemosphere.2009.08.058>.
- Kasambala, H.R., Rwiza, M.J., Mpumi, N., Mwema, M.F., Machunda, R., Mtei, K., Njau, K.K., 2024. 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. *Environ. Challenges* 16, 100975. <https://doi.org/10.1016/j.envc.2024.100975>.
- Kibambe, M.G., Momba, M.N.B., Daso, A.P., Coetzee, M.A.A., 2020. Evaluation of the efficiency of selected wastewater treatment processes in removing selected perfluoroalkyl substances (PFASs). *J. Environ. Manag.* 255, 109945. <https://doi.org/10.1016/j.jenvman.2019.109945>.
- Kurwadkar, S., Dane, J., Kanel, S.R., Nadagouda, M.N., Cawdrey, R.W., Ambade, B., et al., 2022. Per- and polyfluoroalkyl substances in water and wastewater: a critical review of their global occurrence and distribution. *Sci. Total Environ.* 809, 151003. <https://doi.org/10.1016/j.scitotenv.2021.151003>.
- Koch, A., Jonsson, M., Yeung, L.W., Karman, A., Ahrens, L., Ekblad, A., Wang, T., 2020. Per- and polyfluoroalkyl-contaminated freshwater impacts adjacent riparian food webs. *Environ. Sci. Technol.* 54 (19), 11951–11960. <https://doi.org/10.1021/acs.est.0c01640>.
- Kwon, H.O., Kim, H.Y., Park, Y.M., Seok, K.S., Oh, J.E., Choi, S.D., 2017. Updated national emission of perfluoroalkyl substances (PFASs) from wastewater treatment plants in South Korea. *Environ. Pollut.* 220, 298–306. <https://doi.org/10.1016/j.envpol.2016.09.063>.
- Lenka, S.P., Kah, M., Padhye, L.P., 2021. A review of the occurrence, transformation, and removal of poly- and perfluoroalkyl substances (PFASs) in wastewater treatment plants. *Water Res.* 199, 117187. <https://doi.org/10.1016/j.watres.2021.117187>.
- Lu, Y., Liang, Y., Zhou, Z., Wang, Y., Jiang, G., 2019. Possible fluorinate alternatives of PFOS and PFOA. *Environ. Sci. Technol.* 53 (24), 14091–14092. <https://doi.org/10.1021/acs.est.9b06323>.
- Ma, T., Ye, C., Wang, T., Li, X., Luo, Y., 2022. Toxicity of per- and polyfluoroalkyl substances to aquatic invertebrates, planktons, and microorganisms. *Int. J. Environ. Res. Publ. Health* 19, 16729. <https://doi.org/10.3390/ijerph192416729>.
- Mhadhbi, L., Rial, D., Pérez, S., Beiras, R., 2012. Ecological risk assessment of perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in marine environment using *Isochrysis galbana*, *Paracentrotus lividus*, *Siriella armata* and *Psetta maxima*. *J. Environ. Monit.* 14 (5), 1375–1382. <https://doi.org/10.1039/C2EM30037K>.
- Morethe, M.F., Mpenyana-Monyatsi, L., Daso, A.P., Okonkwo, O.J., 2024. Unveiling the hidden threat: spatiotemporal trends and source apportionments of per- and polyfluorinated alkyl substances in wastewater treatment plants in South Africa. *Water Sci. Technol.* 89 (1), 71–88. <https://doi.org/10.2166/wst.2023.401>.
- Mudumbi, J.B.N., Ntwampe, S.K.O., Muganza, F.M., Okonkwo, J.O., 2014a. Perfluorooctanoate and perfluorooctane sulfonate in South African river water. *Water Sci. Technol.* 69 (1), 185–194. <https://doi.org/10.2166/wst.2013.566>.
- Mudumbi, J.B.N., Ntwampe, S.K.O., Muganza, M., Rand, A., Okonkwo, J.O., 2014b. Concentrations of perfluorooctanoate and perfluorooctane sulfonate in sediment of Western Cape Rivers, South Africa. *Carpeth. J. Earth Environ. Sci.* 9, 147–158. <http://hdl.handle.net/11189/5240>.
- Munné, A., Solà, C., Ejarque, E., Sanchís, J., Serra, P., Corbella, I., et al., 2023. Indirect potable water reuse to face drought events in Barcelona city. Setting a monitoring procedure to protect aquatic ecosystems and to ensure a safe drinking water supply. *Sci. Total Environ.* 866, 161339. <https://doi.org/10.1016/j.scitotenv.2022.161339>.
- Newsted, J.L., Holem, R., Hohenstein, G., Lange, C., Ellefson, M., Reagan, W., Wolf, S., 2017. Spatial and temporal trends of poly- and perfluoroalkyl substances in fish fillets and water collected from pool 2 of the Upper Mississippi River. *Environ. Toxicol. Chem.* 36 (11), 3138–3147. <https://doi.org/10.1002/etc.3891>.
- Ngeno, E., Ongulu, R., Orata, F., Matovu, H., Shikuku, V., Onchiri, R., et al., 2023. Endocrine disrupting chemicals in wastewater treatment plants in Kenya, East Africa: concentrations, removal efficiency, mass loading rates and ecological impacts. *Environ. Res.* 237, 117076. <https://doi.org/10.1016/j.envres.2023.117076V>.
- O'Connor, J., Mickan, B.S., Siddique, K.H., Rinklebe, J., Kirkham, M.B., Bolan, N.S., 2022. Spatial, chemical, and microbial contaminants in food waste management for soil application: a review. *Environ. Pollut.* 300, 118860. <https://doi.org/10.1016/j.envpol.2022.118860>.
- Ojemaye, C.Y., Petrik, L., 2019. Occurrences, levels and risk assessment studies of emerging pollutants (pharmaceuticals, perfluoroalkyl and endocrine disrupting compounds) in fish samples from Kalk Bay harbour, South Africa. *Environ. Pollut.* 252, 562–572. <https://doi.org/10.1016/j.envpol.2019.05.091>.
- Ololade, I.A., 2014. Spatial distribution of perfluorooctane sulfonate (PFOS) in major rivers in southwest Nigeria. *Toxicol. Environ. Chem.* 96, 1356–1365. <https://doi.org/10.1080/02772248.2015.1028409>.
- Ololade, I.A., Oladoja, N.A., Ololade, O.O., Oloye, F.F., Adeola, A.O., Alabi, A.B., et al., 2018. Geographical distribution of perfluorooctanesulfonate and perfluorooctanoate in selected rivers from Nigeria. *J. Environ. Chem. Eng.* 6 (4), 4061–4069. <https://doi.org/10.1016/j.jece.2018.06.020>.
- Orata, F., Maes, A., Werres, F., Wilken, R.D., 2011. Perfluorinated compounds distribution and source identification in sediments of Lake Victoria Gulf Basin. *Soil Sediment Contam.* 20, 129–141. <https://doi.org/10.1080/15320383.2011.546442>.
- Orata, F., Quinete, N., Werres, F., Wilken, R.-D., 2009. Determination of perfluorooctanoic acid and perfluorooctane sulfonate in Lake Victoria Gulf water. *Bull. Environ. Contam. Toxicol.* 82, 218–222. <https://doi.org/10.1007/s00128-008-9543-1>.
- Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372, n71. <https://doi.org/10.1136/bmj.n71>.
- Qu, Y., Huang, J., Willand, W., Weber, R., 2020. Occurrence, removal, and emission of per- and polyfluorinated alkyl substances (PFASs) from chrome plating industry: a case study in Southeast China. *Emerging Contam.* 6, 376–384. <https://doi.org/10.1016/j.emcon.2020.10.001>.
- Rickard, B.P., Rizvi, I., Fenton, S.E., 2022. Per- and poly-fluoroalkyl substances (PFAS) and female reproductive outcomes: PFAS elimination, endocrine-mediated effects, and disease. *Toxicology* 465, 153031. <https://doi.org/10.1016/j.tox.2021.153031>.
- Ripanda, A.S., Rwiza, M.J., Nyanza, E.C., Njau, K.N., Vuai, S.A., Machunda, R.L., 2021. A review on contaminants of emerging concern in the environment: a focus on active chemicals in Sub-Saharan Africa. *Appl. Sci.* 12 (1), 56. <https://doi.org/10.3390/app12010056>.
- Shafique, U., Schulze, S., Slawik, C., Böhme, A., Paschke, A., Schüürmann, G., 2016. Perfluoroalkyl acids in aqueous samples from Germany and Kenya. *Environ. Sci. Pollut. Res.* 24 (12), 11031–11043. <https://doi.org/10.1007/s11356-016-7076-4>.
- Shehu, Z., Nyakairu, G.W.A., Tebandeke, E., Odume, O.N., 2022. Overview of African water resources contamination by contaminants of emerging concern. *Sci. Total Environ.* 852, 158303. <https://doi.org/10.1016/j.scitotenv.2022.158303>.
- Simukoko, C.K., Mwakalapa, E.B., Muzandu, K., Mutoloki, S., Evensen, Ø., Ræder, E.M., Lyche, J.L., 2023. Persistent organic pollutants (POPs) and per- and polyfluoroalkyl substances (PFASs) in liver from wild and farmed tilapia (*Oreochromis niloticus*) from Lake Kariba, Zambia: levels and geographic trends and considerations in relation to environmental quality standards (EQSs). *Environ. Res.* 232, 116226. <https://doi.org/10.1016/j.envres.2023.116226>.
- Sinclair, G.M., Long, S.M., Jones, O.A.H., 2020. What are the effects of PFASs exposure at environmentally relevant concentrations? *Chemosphere* 258, 127340. <https://doi.org/10.1016/j.chemosphere.2020.127340>.
- Sindik, Omotayo, Francis Orata, Roland Weber, and Oladele Osibanjo. Per- and polyfluoroalkyl substances in selected sewage sludge in Nigeria. *Chemosphere* 92(3): 329–335. <https://doi.org/10.1016/j.chemosphere.2013.04.010>.
- Spyrou, A., Vlastos, D., Antonopoulou, M., 2024. Evidence on the genotoxic and ecotoxic effects of PFOA, PFOS and their mixture on human lymphocytes and bacteria. *Environ. Res.* 248, 118298. <https://doi.org/10.1016/j.envres.2024.118298>.
- Ssebugere, P., Sillanpää, M., Matovu, H., Wang, Z., Schramm, K.-W., Omwoma, S., Wanasolo, W., Ngeno, E.C., Odongo, S., 2020. Environmental levels and human body burdens of per- and poly-fluoroalkyl substances in Africa: a critical review. *Sci. Total Environ.* 739, 139913. <https://doi.org/10.1016/j.scitotenv.2020.139913>.
- Stockholm Convention, 2019. Feedback terms of use privacy statement. International Institute for Sustainable Development. Summary of the Meetings of the Conferences of the Parties to the Basel, Rotterdam, and Stockholm Conventions. (Accessed 11 January 2024).
- UNEP, 2017. Global Monitoring Plan for Persistent Organic Pollutants Under the Stockholm Convention Article 16 on Effectiveness Evaluation, pp. 1–129. (Accessed 3 December 2023).

- Verhaert, V., Newmark, N., D'Hollander, W., Covaci, A., Vlok, W., Wepener, V., Addo-Bediako, A., Jooste, A., Teuchies, J., Blust, R., Bervoets, L., 2017. Persistent organic pollutants in the Olifants River Basin, South Africa: bioaccumulation and trophic transfer through a subtropical aquatic food web. *Sci. Total Environ.* 586, 792–806. <https://doi.org/10.1016/j.scitotenv.2017.02.057>.
- Wang, L., Yang, T., Liu, X., Liu, J., Liu, W., 2024. Critical evaluation and meta-analysis of ecotoxicological data on per-and polyfluoroalkyl substances (PFAS) in freshwater species. *Environ. Sci. Technol.* 58, 17555–17566. <https://doi.org/10.1021/acs.est.4c04818>.
- Yadav, S., Ibrar, I., Al-Juboori, R.A., Singh, L., Ganbat, N., Kazwini, T., Karbassiyazdi, E., Samal, A.K., Subbiah, S., Altaee, A., 2022. Updated review on emerging technologies for PFASs contaminated water treatment. *Chem. Eng. Res. Des.* 182, 667–700. <https://doi.org/10.1016/j.cherd.2022.04.009>.
- Yu, Y., Kumar, M., Bolan, S., Padhye, L.P., Bolan, N., Li, S., et al., 2023. Various additive release from microplastics and their toxicity in aquatic environments. *Environ. Pollut.* 123219. <https://doi.org/10.1016/j.envpol.2023.123219>.
- Zhang, W., Pang, S., Lin, Z., Mishra, S., Bhatt, P., Chen, S., 2021. Biotransformation of perfluoroalkyl acid precursors from various environmental systems: advances and perspectives. *Environ. Pollut.* 272, 115908. <https://doi.org/10.1016/j.envpol.2020.115908>.
- Zhuo, Y., He, J., Li, W., Deng, J., Lin, Q., 2023. A review on takeaway packaging waste: types, ecological impact, and disposal route. *Environ. Pollut.* 337, 122518. <https://doi.org/10.1016/j.envpol.2023.122518>.
- Zodrow, J., Frenchmeyer, M., Dally, K., Osborn, E., Anderson, P., Divine, C., 2020. Per- and polyfluoroalkyl substances ecological risk-based screening levels (SERDP Contract Report ER18-1653). <https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/ER18-1653>. (Accessed 19 October 2024).