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Risks posed by per- and polyfluoroalkyl substances (PFAS) on the African continent, with an emphasis on aquatic ecosystems

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EDITOR'S NOTE: This article is part of the special series "Ecological Risk Assessment for Per- and Polyfluorinated Alkyl Substances." The series documents and advances the current state of the practice, with respect to ecotoxicological research, environmental exposure monitoring and modeling, ecologically based screening benchmarks, and risk assessment frameworks.

Risks posed by per- and polyfluoroalkyl substances (PFAS) on the African continent, with an emphasis on aquatic ecosystems

ABSTRACT

Per- and polyfluoroalkyl substances (PFASs) are organic pollutants that may pose adverse effects on the ecosystem. Despite their global presence, there is currently still limited knowledge on PFAS on the African continent as monitoring of PFAS is challenging and often not feasible due to the lack of analytical capacity and high costs. However, there is a need to understand the environmental risks posed by these chemicals in developing countries, as increasing urbanization will likely lead to an increase of PFAS contamination in the environment. Although as far as known PFAS concentrations in the African aquatic environment are generally low compared to more developed countries in the world, exceedances of ecological quality standards (EQS) were reported in a few cases, providing evidence for potential ecological risks at these ecosystems. However, the number of ecosystems at risk will likely increase due to the increasing urbanization and modernization of African countries. Therefore, environmental regulations should be updated and implemented to reduce any further contamination of the aquatic environment with these chemicals. In addition, analytical laboratories in Africa should develop their capacity to detect PFAS and related compounds regularly and on a routine basis. Local hotspots need to be identified, the influence of these hotspots on the PFAS burden in the environment should be investigated, and environmental regulations should be implemented for these hotspots in order to reduce their environmental impact. Therefore, we recommend a more routine monitoring of PFAS, including new PFAS that are currently used as PFOA and PFOS alternatives, not regulated and of environmental concern.

Keywords: Perfluoroalkyl acids; Africa; ecological risk; aquatic; environmental regulations

INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are chemicals that are globally distributed in the environment due to direct manufacturing, applications in consumer products, transformation of precursor compounds and gas- and particle-phase atmospheric long-range transport (Barber et al. 2007; Buck et al. 2011). Despite their global presence, little is known on PFAS pollution on the African continent and the ecological risks they pose to its rich biodiversity and critical ecosystem services (Ssebugere et al. 2020). The African biodiversity and ecosystem services are also threatened by other environmental stressors (Egoh et al. 2012) such as legacy organochlorine pesticides (Ansara-Ross et al. 2012; Olisah et al. 2020), dioxins and furans (Sseburgere et al. 2019), and pharmaceuticals and personal care products (Gwenzi and Chaukura 2018; K'oreje et al. 2020).

The increasing modernization and importation of PFAS-containing consumer products in developing countries may lead to an increase of PFAS contamination in the environment. The limited knowledge of PFAS on the African continent is because monitoring of PFAS is challenging and often not feasible due to the lack of analytical capacity and high costs (Sindiku et al. 2013; Ssebugere et al. 2020). Many laboratories in Africa have gas chromatography/mass spectrometry (GC/MS) and ultraviolet-visible (UV-VIS)-based methods for instrumental analyses of pollutants, which are less suitable for PFAS monitoring than ultra-performance liquid chromatography/tandem mass spectrometry (UPLC-MS; Ssebugere et al. 2020; UNEP 2014).

However, there is a need to understand the fate and environmental risks posed by these substances in developing countries, and therefore data need to be generated for a preliminary understanding of the environmental risks PFAS pose in these countries (Sindiku et al. 2013;

Ssebugere et al. 2020). Furthermore, these data will allow for better decision making regarding the establishment, adjustment and implementation of regulatory measures towards environmental management of these chemicals on the African continent. In this study, we aim to investigate the current environmental risk status associated with PFAS pollution in the African aquatic environment, the need for more investigation and environmental monitoring, and the need to establish, adjust and/or implement environmental regulations in these countries.

PFAS REGULATIONS IN AFRICA

The global distribution and potential effects of PFAS have resulted in a global concern on these chemicals since the late 1990s, especially after evidence had accumulated that some PFAS were not only ubiquitous in various biological and environmental matrices but also highly persistent and able to biomagnify in the food chain (Giesy and Kannan 2001). Their bioaccumulative, persistence and toxic potential has resulted in global efforts to reduce environmental exposure to these chemicals. For example, in 2009, perfluorooctane sulfonate (PFOS) and perfluorooctane sulfonyl fluoride (POSF) were listed in the Stockholm Convention on persistent organic pollutants (POPs) for global restriction in their production and use (Stockholm Convention 2008). Additionally, perfluorooctanoic acid (PFOA), its salts and PFOA-related products were included in Annex A of this Convention (Stockholm Convention 2019), and perfluorohexane sulfonate (PFHxS) and its salts are currently under review for the Convention.

Although many African countries endorsed the Stockholm Convention and developed National Implementation Plans (NIPs), efforts taken among countries to minimize PFAS exposure vary. The NIPs were often developed before 2009, hence before the listing of PFAS in the Convention, and many have not been updated since (Ssebugere et al. 2020). Therefore, PFAS are often not included in these NIPs. However, some countries are updating their regulations concerning PFAS. For example, in South Africa regulations have been promulgated that PFOS, POSF and PFOS-containing products are set to be phased-out by December 2021 (South African Government Gazette 2019). Whilst international studies on PFAS date back to the 1990s, studies on PFAS in aquatic (water, sediment and fish) as well as terrestrial ecosystems (crops, wildlife, human food and blood, etc.) in Africa have only recently started appearing in the international literature (Ssebugere et al. 2020). Most countries face difficulties in including this "new" group of pollutants, from an African perspective, into their environmental management frameworks. Although the regulation of hazardous substances is well structured through environmental legislation in countries like South Africa (Meyer and Roos 2015), chemical specific management requires definition of environmental quality criteria for those substances (Claassens et al. 2020).

ENVIRONMENTAL QUALITY STANDARDS AND GUIDELINES FOR FRESHWATER, SEDIMENT AND AQUATIC BIOTA

Although most regulatory attention focuses on human health risks caused by PFAS contaminated drinking water and groundwater standards, there is a need for continued research on potential risk to non-human biota (McCarthy et al. 2017). Although there is generally a strong base of aquatic toxicity data for environmental risk assessment for many pollutants, data are only available for a few PFAS compounds (mostly PFOA and PFOS). Furthermore, ecological quality standards (EQS) for identifying potential adverse effects to non-human biota are still scarce, especially for organism living in and on freshwater sediments.

The EQS values and predicted no-effect concentrations (PNEC) that are currently available for surface water, sediment and aquatic biota are presented in Table 1. These EQS values were obtained from studies in several countries. In sediment, threshold values (PNEC values) to protect benthic organisms were proposed for sediment quality assessment in France (INERIS 2018). In addition, Casado-Martinez et al. (this issue) determined tentative quality standards to protect pelagic organisms. However, it should be stated that the latter EQS, which was determined based on the Equilibrium Partitioning (EqP) theory for non-ionic organic chemicals (Di Toro et al. 1991) due to the absence of spiked sediment toxicity data, should be treated with caution. PFAS are known to behave differently from non-ionic hydrophobic chemicals, as they are potentially prone to active transport through biological membranes, and hence some of the basic assumptions of this theory were violated (Casado-Martinez et al. this issue).

Zodrow et al. (2020) determined water risk-based screening levels (RBSLs) for aquatic wildlife, based on the No-observed-adverse-effect-level (NOAEL) and lowest-observed-adverse-effect-level (LOAEL). These values were derived in laboratory tests on single species of aquatic organisms with growth, survival/mortality and reproduction/development as endpoints. The Government of Western Australia Department of Environment Regulation (DER) (2016) developed a threshold for identifying potential adverse health effects to aquatic biota exposed to surface water for PFOS, PFOA and perfluorohexane sulfonate (PFHxS) based on the Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (ANZECC/ARMCANZ) water quality guidelines (ANZECC/ARMCANZ 2000). An exceedance of these values indicates that certain species might be at risk due to PFAS pollution, and a conservative management approach should be implemented. Similarly, the Norwegian Pollution Control Authority has classified PFOS concentrations in surface water depending on the expected effects on aquatic biota (NPCA 2008).

The EQS provided in Directive 2013/39/EU of the European parliament included both average standards for PFOS and its salts as well as maximum allowable concentrations in surface waters (EU 2013). However, these values are not necessarily ecological risk based (McCarthy et al. 2017). In addition to these EQS, the EU directive also included a specific biota threshold, which is determined in fish (EU 2013).

ENVIRONMENTAL RISKS DUE TO PFAS POLLUTION IN AFRICA

Due to the lack of data from many African countries, the results discussed here should be interpreted with caution as they may not be representative for the entire African continent. PFAS concentrations in the African environment are known to be highly variable between different geographical areas; hence, the discussed ecological risks posed by PFAS are not applicable to the entire continent, as they are affected by numerous factors (e.g. different sources/degree of urbanization/etc.) (Hanssen et al. 2010; Ssebugere et al. 2020). As mentioned before, the lack of instrumental capacity for PFAS analyses in African countries provides a need for African laboratories to develop their analytical capacities in order to continue monitoring PFAS and investigate where PFAS might pose an environmental risk. In addition, expertise in operating these advanced instrumentation, such as UPLC-MS, is still lacking in most African laboratories (Gwenzi and Chaukura 2018). Although nations of the African Union have pledged to dedicate 1% of their Gross Domestic Products (GDPs) to research and development, these nations often struggle with other competing priorities (e.g. education and food) (Marincola and Kariuki 2020). Furthermore, commercial funders often do not fund basic research, African governments have no resources to fill this gap, and Western funders mainly focus on health and medical research (Marincola and Kariuki 2020). Hence, according to Marincola and Kariuki (2020) the lack of funding and appropriation of existing funds to competing priorities remain a major challenge to developing and implementing the necessary human capital and infrastructure to address environmental issues on the continent.

In general, most studies examining PFAS concentrations in African aquatic ecosystems report concentrations at the nanogram level (ng/g or ng/L) for most samples (Table 2; Ssebugere et al. (2020) for a detailed summary of all PFAS concentrations in African countries). In the majority of the matrices, these concentrations are lower compared to more developed regions in the world. Nonetheless, in some areas, the PFAS concentrations in the environment were sometimes high enough to exceed one or more of the quality standards that are presented in Table 1. We have summarized these concentrations in Table 2 and refer to Ssebugere et al. (2020) for a detailed summary of all PFAS concentrations, including those lower than the quality standard values, reported in Africa.

The PFOS concentrations in sediments from the Diep and Eerste Rivers in South Africa (Mudumbi et al. 2014) and in multiple rivers in the Lake Victoria Basin in Kenya (Orata et al. 2011) exceeded the EQS values for sediment to protect pelagic species (Casado-Martinez et al. this issue). The concentrations in sediments of the Diep and Eerste Rivers also exceeded the threshold value set to protect benthic organisms (INERIS 2018).

In surface waters, the PFOS concentrations in the Lake Victoria Gulf in Kenya (Orata et al. 2009), multiple Nigerian rivers (Ololade 2014, Ololade et al. 2018) and multiple South African rivers, i.e. Plankenburg River (Fagbayigbo et al. 2018), Vaal River (Groffen et al. 2018), Salt River and Eerste River (Mudumbi et al. 2013) exceeded the EQS for high conservation value freshwater ecosystems (ANZECC/ARMCANZ 2000). In addition, the PFOS concentrations in the Diep River

(Mudumbi et al. 2013) and in the Pra and Kakum Rivers in Ghana (Essumang et al. 2017) exceeded the EQS for slightly disturbed systems (ANZECC/ARMCANZ 2000) and the NOAEL-based minimum wildlife RBSL (Zodrow et al. 2020). Furthermore, in all these studies, the PFOS concentrations are higher than the EQS determined for secondary poisoning of top predators (EC 2011). The EQS levels for PFBS, PFHxS, PFBA, PFHxA, PFOA and PFNA were never exceeded in surface water of African rivers.

Regarding the EU directives guideline for biota, only PFOS concentrations observed in fish from Winam Gulf in Lake Victoria, Kenya (Francis et al. 2008) and in invertebrates and fish from the Vaal River, South Africa (Groffen et al. 2018) exceeded this guideline. Furthermore, the median PFOS concentrations in the plasma of Nile crocodiles from multiple sites in South Africa exceeded the biota EQS (Christie et al. 2016). However, it should be borne in mind that this EQS was developed for fish and it is uncertain whether it will provide protection for other aquatic organisms such as reptiles and invertebrates. None of the other studies on African aquatic biota reported concentrations that exceeded the EQS values (as reviewed by Ssebugere et al. 2020).

Based on the PFAS concentrations in the water, most of the studied African aquatic ecosystems can be considered slightly- to moderately disturbed and toxicological implications are expected to be limited. However, the exceedances of the EU directive biota guidelines (EU 2013) and the sediment thresholds to protect benthic and pelagic organisms, show that there is a potential risk to biota in some of the studied South African rivers.

Pollution sources of PFAS in Africa are often not clearly identified. To the best of our knowledge, only Pelchem, in South Africa, is an identified fluorochemical industrial company. However, it is still unclear whether this could be considered a point-source, as they do not manufacture PFAS themselves (Ssebugere et al. 2020). It has been hypothesized in numerous African studies that wastewater treatment plants, industrial discharge and the presence of urbanization have contributed to the PFAS pollution in the aquatic ecosystem (Essumang et al. 2017; Fagbayigbo et al. 2018; Groffen et al. 2018; Ololade et al. 2018).

Existing studies show that African urban areas have much higher levels of PFAS than rural areas (Ssebugere et al. 2020), as they tend to have more access to PFAS-containing consumer products (Hanssen et al. 2010). Hence, the current general low level of PFAS may significantly increase with urbanization. Indeed, Africa is reported to have one the highest urbanization rate in the world, with its urban population likely to more than triple from 395 million in 2010 to 1.339 billion by 2050 (Güneralp et al. 2017). Therefore, it is likely that PFAS concentrations will increase, thereby increasing the risks posed to aquatic ecosystems that have PFAS concentrations exceeding, or close to exceeding, EQS values.

CONCLUSION

The presence of PFAS in the African aquatic environment is likely the result of an uncontrolled importation and use of PFAS-containing products and inadequate legislation (Ssebugere et al. 2020). Although the concentrations in the African aquatic environment are generally low compared to those in more developed countries, exceedances of EQS suggest that ecological risks might already occur and that concentrations potentially will increase over time with urbanization. Therefore, outdated regulations should be updated and new ones should be implemented to reduce the risks posed by these chemical to the African aquatic environment.

In addition, laboratories in African countries should develop capacities to analyze for PFAS and related compounds. Local hotspots need to be identified, the influence of these hotspots on the PFAS burden in the environment should be investigated, and environmental regulations should be implemented for these hotspots to reduce their environmental impact. Without sufficient legislation and management, the environmental risks of PFAS are likely to increase due to bioaccumulation and biomagnification in the aquatic food chain (Munoz et al. 2017). Therefore, we recommend a more routine based monitoring of PFAS, including new PFAS that are currently used as PFOA and PFOS alternatives, not regulated and of environmental concern (Brendel et al. 2018).

TABLE CAPTIONS

Table 1. Ecological quality standards (EQS) of PFAS for freshwater, sediment and aquatic biota.1Values represent PNEC concentrations.

Matrix	PFBS	PFHxS	PFOS	PFBA	PFHxA	PFOA	PFNA	Remark	Ref.
Sediment (ng/g)			67					5% total organic carbon (TOC) content. Threshold to protect benthic organisms.	INERIS (2018)
			25					5% TOC. Threshold to protect pelagic organisms.	Casado-Martinez et al. (this issue)
Freshwater (ng/L)		0.23	0.23			19000		High conservation value systems	Western Australia DER (2016) ANZECC/ARMCANZ (2000)
		130	130			220000		Slightly – moderately disturbed systems	
		2000	2000			632000		Highly disturbed systems (90% species protection)	
		31000	31000			1824000		Highly disturbed systems (80% species protection)	
			<25000					No toxic effects	NPCA (2008)[1]
			25000 – 72000					Chronic effects by long-term exposure	
			72000 – 360000					Acute toxic effects by short-term exposure	
			>36000					Severe acute effects	
			0.65					Annual average standard for inland surface waters	EU (2013)
			36000					Maximum allowable concentration	
			230					EU TGD, based on NOEC for *Chironomus sp.* emergence	EC (2011) and Moermond et al. (2010)
			2					EU TGD derived for secondary poisoning for top predators	EC (2011)
	640000		75	470000	210000	44000	22000	NOAEL-based minimum wildlife RBSL.	Zodrow et al. (2020)
	1100000		360	470000	440000	89000	29000	LOAEL-based minimum wildlife RBSL	Zodrow et al. (2020)
Biota (µg/kg ww)		-	9.1			-		This value was determined using fish	EU (2013)

Table 2. PFAS concentrations reported in African freshwater environments for which one or more of the environmental quality standards (EQS), reported in Table 1, for a specific matrix are exceeded. Only compounds for which a EQS was reported in Table 1 are included.

Matrix	**River, Country**	**Year of sampling**	**PFBS**	**PFHxS**	**PFOS**	**PFBA**	**PFHxA**	**PFOA**	**PFNA**	**Ref.**
Sediment (µg/kg)	Diep River, South Africa	2011			2.53 - 121					Mudumbi et al. (2014)
	Eerste River, South Africa	2011			0.75 – 75.1					Mudumbi et al. (2014)
	Rivers in Lake Victoria Basin, Kenya	2008			<1 – 57.5					Orata et al. (2011)
Freshwater (ng/L)	Lake Victoria Gulf, Kenya	2006 - 2007			<0.4 – 2.53			<0.4 – 11.7		Orata et al. (2009)
	Multiple rivers, Nigeria	2014			1.7 – 16.2					Ololade, 2014
	Multiple rivers, Nigeria	2016			3.9 – 10.1			0.8 – 2.8		Ololade et al. (2018)
	Plankenburg River, South Africa	2014	<LOQ		<0.06 – 12.4	10.2 – 28.4		12.8 – 62.6	<LOQ	Fagbayigbo et al. (2018)
	Vaal River, South Africa	2014	<LOQ – 24.7	<LOQ – 7.6	0.4 – 35.7		<LOQ – 20.3	0.6 – 4.6	<LOQ – 1.8	Groffen et al. (2018)
	Salt River, South Africa	2011			<LOD – 47			0.7 – 390		Mudumbi et al. (2013)
	Eerste River, South Africa	2011			<LOD – 23			3.4 – 146		Mudumbi et al. (2013)
	Diep River, South Africa	2011			<LOD - 183			1.7 - 314		Mudumbi et al. (2013)
	Pra and Kakum Rivers, Ghana	2015			77.2 - 277			1.78 – 321		Essumang et al. (2017)
Fish (µg/kg)	Winam Gulf Lake Victoria, Kenya	2007			0.9 – 35.7					Francis et al. (2008)
	Vaal River, South Africa	2014			<0.12 – 45.7					Groffen et al. (2018)
Invertebrates (µg/kg)	Vaal River, South Africa	2014			<LOQ – 35.5					Groffen et al. (2018)
Nile Crocodiles plasma (µg/kg)	Multiple sites, South Africa	2012 - 2013			0.776 – 118					Christie et al. (2016)

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