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Review

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Waste streams as current sources of persistent organic pollutants and organophosphate esters in Africa - a critical review

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Abstract

Per- and polyfluoroalkyl substances, chlorinated paraffins, brominated flame retardants, polychlorinated biphenyls and mirex are regulated under the United Nations Environment Programme's (UNEP's) Stockholm Convention on Persistent Organic Pollutants (POPs) intended for the eradication of hazardous contaminants in the environment. There is also a major concern for organophosphate esters and specific alternative or novel brominated flame retardants. To date, no evidence exists that major producers of these chemicals occur on the African continent. They are understood to find their way into African environments through the import of commercial products, in particular products with second-hand value and short lifespans, which may enter waste streams in a relatively shorter period. To further understand the current levels of these selected contaminants in African waste streams, existing documents capturing various African waste stream compartments for the above outlined targeted contaminants were gathered from an exhaustive literature review. Key factors influencing the transfer of contaminants from waste or elevated concentrations of contaminants in African waste streams are associated with the nature and/or sources of contaminants, volume of contaminants or waste in relation to the capacity of treatment plants/landfills, condition or age of treatment plants/landfill geomembrane liner, model adopted for contaminants removal and treatment procedures for collected sludges or leachates. Evidence from the selected studies indicates substantial POP contamination in African landfills and dumpsites, wastewater effluents/sludge

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and human/biological samples around dumpsites and landfills. Unfortunately, the continent has inadequate infrastructural capacity to adequately handle POP in the waste streams. This review provides recommendations and suggestions for future studies.

Keywords: Landfills, dumpsites, wastewater treatment plants, sewage sludge

INTRODUCTION

Persistent organic pollutants (POPs) are notorious environmental chemicals characterised by their toxicity, long-range environmental transportation and bioaccumulation. Although there is uncertainty on the specific number of chemicals with POP characteristics in the environment, 26 chemicals are presently listed in Annex A of the United Nations Environment Programme (UNEP) under the Stockholm Convention on Persistent Organic Pollutants aimed at eradicating harmful chemicals. Among these pollutants are perfluorooctanoic acid (PFOA) and its related compounds, short-chain chlorinated paraffins, polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs) and mirex (dechlorane)[1]. Additionally, concerns are growing for alternative or novel brominated flame retardants, such as decabromodiphenyl ethane, used as replacements for the legacy brominated flame retardants (BFRs). Although organophosphate esters (OPEs) do not meet the persistence requirements to be classed as POPs under the Stockholm Convention, several epidemiological studies have evidenced severe health risks, such as endocrine disruption and cancer[2,3].

These chemicals have a wide range of applications, particularly in electrical and electronic equipment, building and construction materials and textiles[4,5], in use across the African continent. However, there is no evidence of major producers of these chemicals in Africa[6,7]. The presence of POPs and OPEs in the African environment is possible through the use of the aforementioned commercial products[8], waste transfer from developed and developing nations[9] and long-range atmospheric transport from other continents. Unfortunately, due to limited financial capacity, many African populations rely on commercial products of second-hand value with a potential implication of shorter lifespans and subsequently are sent to the waste stream, in shorter time periods. Waste streams can be viewed as both possible reservoirs and sources for POPs and OPEs in Africa.

Per- and polyfluoroalkyl substances (PFAS), chlorinated paraffins (CPs), BFRs, PCBs, OPEs and mirex have been observed in various environmental media in Africa, including air[7,10,11], dust samples[12,13], soil[14,15] and water[16-18], as well as in human samples[19-21]. However, waste streams (complete paths of wastes from their sources to recovery, recycling or final disposal) have indicated excessive concentrations of POPs in many studies[22], including in Africa[22,23].

As of November 2021, 33 of the 47 territories on the African continent are categorised by the United Nations as least developed countries (LDCs)[24]. Most African nations have limited infrastructures and capabilities for adequate waste management. Current waste management practices and policies targeting wastes in Africa can vary considerably depending on the economic situation of the country. The implications of this are potential adverse impacts of waste streams on the environment and increasing risks of exposure to these contaminants through ingestion of contaminated food, groundwater sources and indoor/outdoor dust particles, together with inhalation of contaminated outdoor/indoor air. In addition, African waste streams are possibly key contributors to global sources of regulated compounds. This is possible through the net emission of multiple cycles of untreated/poorly treated wastes and, as a result, can potentially lead to global circulation through air diffusion, due to warm African environmental climates,

and through contamination of ocean resources.

The current paper aims to review the available data on the contamination of African waste streams with POPs and OPEs. The aims of this review are: (1) to summarise current published data on the occurrence of POPs and OPEs in African waste streams; (2) to identify the potential factors influencing releases of POPs and OPEs from waste streams to the African environment; and (3) to highlight significant research gaps that require further investigation.

METHODS

The key inclusion criteria in selecting articles for this study were specifically POP and OPE contamination deriving from African waste streams and related environmental media directly linked to waste stream activities. Research articles, reviews and book chapters from Google Scholar and Web of Science Core Collection electronic databases were explored between March and May 2022 using the search terms of the individual chemicals of PFAS, CPs, BFRs, alternative and novel flame retardants, PCBs, OPEs and mirex, in conjunction with waste (or landfill) and Africa or specific names of the African countries. After the assessment of multiple entries using these search criteria, 212 documents were obtained for review and further screening. The qualities of the articles were further investigated in line with the target criteria of specifically reporting PFAS, CPs, BFRs, PCBs, OPEs, mirex and alternative flame retardants on African wastewater treatment plants (WWTPs), landfills, dumpsites and their surroundings between 2000 and 2022. In total, 47 documents from 12 countries [Figure 1] were finally selected for the current study.

CONCENTRATIONS REPORTED FOR SELECTED CONTAMINANTS IN AFRICAN DUMPSITES AND LANDFILLS

Concentrations reported in air from dumpsites and landfills

In total, 35 research articles were found to report the selected contaminants for about 50 African landfills or dumpsites [Supplementary Table 1]. The reported concentrations are summarised in Table 1, while the concentrations for the individual compounds are summarised in Supplementary Tables 2-6. In South Africa, Katima *et al.* reported high concentrations of alternative flame retardants (AFRs) comprising 2-ethyl-hexyl tetrabromobenzoate (EHTBB), bis(2-ethylhexyl) tetrabromophthalate (BEHTBP) and 1, 2-bis(2,4,6-tribromophenoxy)ethane (BTBPE) as 4.7 ng/m^3 in air at landfill sites[25]. In the same study, high concentration ranges of 0.050-12 and 0.95-2.8 ng/m^3 were reported for hexabromocyclododecane (HBCDD) and $\sum_9$BDEs, respectively. These concentrations exceeded the concentrations reported in the same studies for the industrial and highly populated locations. DecaBDE (BDE-209), PentaBDE (BDE-99 and BDE-100) and AFRs (EHTBB, BEHTBP and BTBPE,) congeners were dominant compounds reported in all seasons, with a suggestion that these congeners have been extensively used in consumer products. The authors attributed the high concentrations of the contaminants to the lack of treatment (besides compaction) of brominated flame retardant (BFR) wastes at the disposal sites. The concentrations of HBCDD, PBDEs and AFRs in the landfill air were reported to be higher in summer than winter due to warmer temperatures in summer intensifying BFR volatilisation emission rates from landfilled waste.

Hogarh *et al.* reported the highest concentrations for $\sum_{190}$PCBs 4.6 ng/m^3 in air samples collected from Agbogbloshie. Agbogbloshie is a huge scrapyard and dumpsite location in central Accra, Ghana, infamous for informal waste electrical and electronic equipment (WEEE) recycling activities[26]. In particular, excessive polychlorinated biphenyl (PCB) concentrations (11 ng/m^3) were reported from a plume resulting from uncontrolled open burning of WEEE. The tri-PCBs were reported to dominate these PCB concentrations. Using statistical source apportionment, the authors concluded that the WEEE recycling site is a major source of atmospheric PCBs in Ghana. Adesina[27] similarly reported high concentrations of $\sum_{15}$PCBs 3.1-5.0 ng/m^3 around open burning

Table 1. Summary of the reports on landfill/Dumpsite (concentrations in ng/L for leachate or water, ng/g for soil or dust and ng/m^3 for air)

Location	Sample number (Study period)	Environmental media	Treatment type	Chemicals	Concentrations-mean (range)	References
Landfill/dumpsite air						
Gauteng Province, South Africa	2016 - 2017 (ns)	Landfill air	-	$\sum_3$AFR	2.0-4.7	[25]
			-	HBCDD	0.05-0.12	
			-	$\sum_9$BDEs	0.95-2.8	
Accra, Ghana	2011 (ns)	Air from burning WEEE site	-	$\sum_{190}$PCBs	4.6-11	[26]
Ado-Ekiti, Nigeria	ns (ns)	Air around burning dumpsite	-	$\sum_{15}$PCBs	3.1-5.0	[27]
Dar es Salaam, Tanzania	2019 (n = 9)	Air around dumpsite & electronic-waste site air	-	Chlorinated paraffins	[s]23(4-59) [m]10(1-33)	[13]
Landfill/Dumpsite soil						
Accra, Ghana	2010 (ns)	WEEE dumpsite soil	-	∑PCBs	[d]5.5	[28]
Accra, Ghana	ns (n = 14)	Soils & plant around WEEE (not quantified)	-	BDEs	BDEs- 28, & 47 (plants & soil)-identified but not quantified	[29]
Accra, Ghana	2015 (n = 18)	WEEE dumpsite soil	-	$\sum_{15}$BDEs	55 (16-97)	[30]
Accra, Ghana	2013 (n = 41)	WEEE dumpsite soil	-	$\sum_8$BDEs	21 -6900	[31]
Accra, Ghana	2015 (n = 15)	WEEE dumpsite soil	-	$\sum_{25}$BDEs	6.3-7700	[23]
	2015 (n = 15)	WEEE dumpsite soil	-	Chlorinated paraffins	[s]3300 (150-28,000) [m]380 (nd-1300)	
	2015 (n = 15)	WEEE dumpsite soil	-	$\sum_7$PCBs	[i]92 (6.5-830)	
Freetown, Sierra Leone	2015 (n = 10)	Dumpsite soil	-	$\sum_{25}$BDEs	1.2-100	
	2015 (n = 10)	Dumpsite soil	-	Chlorinated paraffins	[s]450 (69-1600) [m](220) (nd-1400)	
	2015 (n = 10)	Dumpsite soil	-	$\sum_7$PCBs	[i]4.7 (0.74-43)	
Abia, Lagos, & Oyo, Nigeria	2015 (n = 29)	WEEE dumpsite soil	-	$\sum_{17}$BDEs	**0.0032-21	[32]
Benin City, Nigeria	2017 (n = 30)	WEEE dumpsite soil	-	∑BDEs	*nd-1.9 (mainly BDE-79 found)	[33]
Ile-Ife, Nigeria	-	Dumpsite soil	-	$\sum_6$BDEs	[r]18	[34]
Abuja, Nigeria	ns (n = 96)	Dumpsite soil	-	$\sum_7$BDEs	110-370	[35]
Lagos & Ibadan, Nigeria	ns (ns)	Dumpsite soil	-	$\sum_6$PCBs	3-410	[37]
Ado-Ekiti, Nigeria	ns (ns)	Dumpsite soil	-	$\sum_{15}$PCBs	24-29	[27]
Douala, Cameroun	2017 (n = 30)	WEEE recycling sites soil	-	$\sum_{30}$PCBs	*32-73	[38]
Addis Ababa, Ethiopia	2018-2019 (n = 45)	Soil from dumpsite for transformers	-	$\sum_{18}$PCBs	1000-4900	[39]
Dar es Salaam, Tanzania	2019 (n = 9)	Dumpsite soil	-	Chlorinated paraffins	[s]670(11-5300) [m]970(26-5100)	[13]
Gauteng province, South Africa	ns (n = 6)	Landfill soil	-	$\sum_7$BDEs	(median = 7.3) (7.1-11)	[40]
Calabar, Nigeria	ns (ns)	Dumpsite stimulated leachate	-	$\sum_8$PFASs	[σ]0.05-5.0	[49]

Landfill/Dumpsite sediment						
Gauteng Province, South Africa	2013 (n = 18)	Landfill sediment	Geomembrane liners	$\sum_3$AFR	*#71	[41]
Gauteng Province, South Africa	2013 (n = 18)	Landfill sediment	Geomembrane liners	HBCDD	33	[41]
Gauteng Province, South Africa	2017 (ns)	Landfill sediment	-	$\sum_{10}$OPFRS	630(120-1700)	[43]
			-	$\sum_5$BDEs	0.82-1.4	
			-	$\sum_7$PCBs	2.3-6.9	
Gauteng, South Africa	2013 (ns)	Landfill sediment	-	$\sum_7$BDEs	0.8-8.4	[48]
Gauteng Province, South Africa	2014 (ns)	Landfill sediment	Geosynthetic clay liner	$\sum_9$BDEs	2.5-4.9	[42]
Pretoria, South Africa	ns (ns)	Landfill sediment	-	$\sum_{15}$BDEs	33	[44]
Landfill/Dumpsite leachate						
Gauteng Province, South Africa	2017 (ns)	Landfill leachate	Geosynthetic clay liner	$\sum_{10}$OPFRSs	9700(560-17,000)	[43]
Gauteng Province, South Africa	2013 (n = 18)	Landfill leachate	Geomembrane liners	$\sum_3$AFR	*#0.072	[41]
Gauteng Province, South Africa	2013 (n = 18)	Landfill leachate	Geomembrane liners	HBCDD	0.024	[41]
Gauteng Province, South Africa	2014 (n = 24)	Landfill leachate	-	γ-HBCD	nd-50	[45]
	2014 (n = 24)	Landfill leachate	-	TBBPA	< 0.82	
	2014 (n = 24)	Landfill leachate	-	$\sum_5$BDEs	40-480	
Cape Town, South Africa	2010-2011 (ns)	Landfill leachate	-	$\sum_8$BDEs	340 (0.28-2200)	[46]
Pretoria, South Africa	ns (ns)	Landfill leachate	-	$\sum_{13}$BDEs	8.4-55	[47]
Gauteng, South Africa	2013 (ns)	Landfill leachate	-	$\sum_7$BDEs	0.13-3.7	[48]
Gauteng Province, South Africa	2014 (ns)	Landfill leachate (effluent)	Geosynthetic clay liner	$\sum_9$BDEs	0.32-1.4	[42]
Lagos, Nigeria	ns (ns)	Dumpsite leachate	-	$\sum_6$PCBs	nd-80	[37]
Lagos & Akure, Nigeria	ns (ns)	Dumpsite leachate	-	$\sum_{14}$PCBs	3.0-41	[49]

*#Mean sum of EH-TBB, BTBPE and BEHTBP; *range of mean concentrations; **range of median concentrations; nd: not detect; ns: not specified; [s]short-chain chlorinated paraffins; [σ]sum of PFBS, PFOS, PFHpA, PFOA, PFNA, PFDA, PFUnDA and PFDoDA (max = PFDA; min = PFBS); [m]medium-chain chlorinated paraffins; [P]PFOA; [PP]PFOS; [d]∑dioxin-like PCBs; [I]ICES indicator PCBs; [MT]mean value of the total congeners; [r]individual concentrations of BDEs 28, 47, 99, 100, 153 and 154.

municipal dumpsites in Nigeria, with PCB-52 (mean = 2.3 ng/g) reported as the dominant congener. In Dar es Salaam, Tanzania, high concentrations of short-chain chlorinated paraffins (SCCPs) (4.0-59 ng/m^3) and medium-chain chlorinated paraffins (MCCPs) (1.0-33 ng/m^3) were also reported in air from dumpsite sites[13]. The authors referred to waste handling sites as important emission sources of chlorinated paraffins in the studied urban, suburban and rural locations.

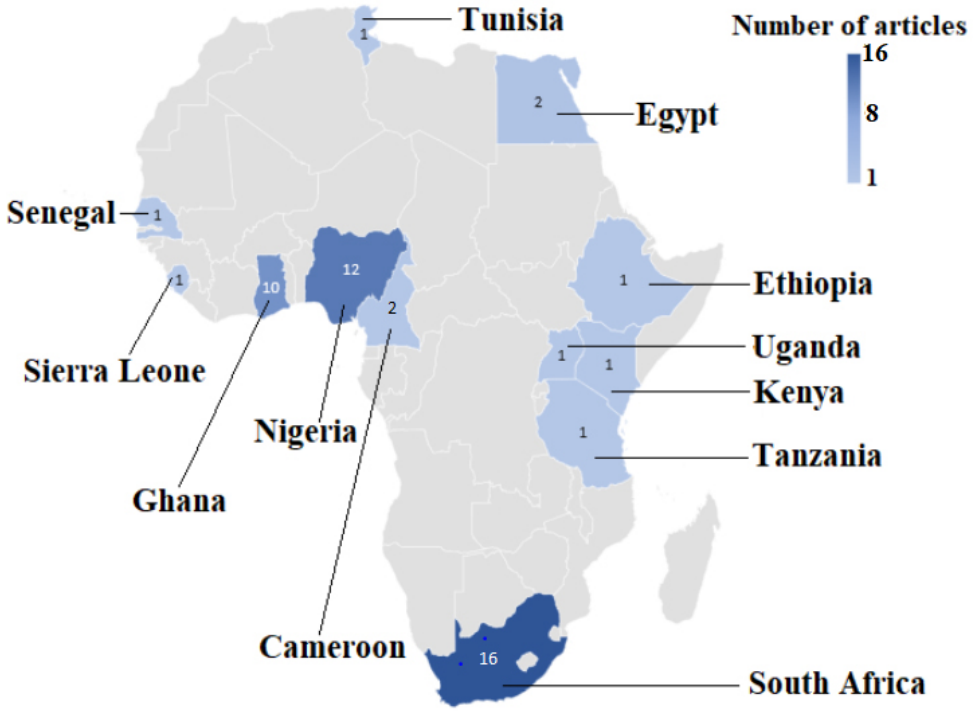

Figure 1. Research articles selected for this study and geographical locations.

Concentrations reported in soil from landfills and dumpsites

Sixteen studies were obtained capturing landfill/dumpsite soils [Table 1]. In a 2010 study, Fujimori *et al.* reported concentrations of dioxin-like PCBs (median = 5.5 ng/g) in soil from Ghana's Agbobgloshie WEEE dumpsite, with sources pointing to the open burning of WEEE[28]. In 2014, Oteng-Ababio *et al.* identified several PBDE congeners (BDE 1, 7, 28, 47, and 99/100) in soil collected from Agbobgloshie WEEE informal recycling site[29]. The highest concentrations of PBDEs were found at burning sites and areas of intense incineration for copper retrieval. The authors raised concern about the possible impacts of emissions of PBDEs from the uncontrolled informal WEEE recycling and dumping activities at Agbobgloshie on local vegetable farm soils. Subsequently, Akortia *et al.* found high PBDE concentrations ($\sum_{15}$BDEs 16-97 ng/g) from the soil of the Agbobgloshie WEEE dumpsite directly related to the informal WEEE recycling activities present in 2017[30]. Sources of lower-brominated PBDEs not usually utilised in treating electrical and electronic goods, such as BDE-28, were most likely due to the debromination of more commonly used higher-brominated PBDE congeners formed during high-temperature burning conditions from low-tech recycling operations. Similarly, Tue *et al.* also reported high concentrations of PBDEs in soils from the Agbobgloshie WEEE Site in 2019, with $\sum_{8}$BDEs ranging from 21-6900 ng/g. Concentrations were specifically reported to be higher in dismantling areas when compared to the areas of burning[31]. However, generally, the concentrations in these two areas were reported to be greater than for soils collected from locations other than directly from the Agbobgloshie WEEE dumpsite.

From an earlier 2015 investigation of the Agbobgloshie WEEE site, Möckel *et al.* reported 6.3-7700 ng/g $\sum_{25}$ BDEs, 150-28,000 ng/g SCCPs, 1300 ng/g MCCPs and 6.5-830 ng/g $\sum_{7}$PCBs[23]. Additionally, concentrations of $\sum_{25}$BDEs (1.2-100 ng/g), SCCPs (69-1,600 ng/g), MCCPs (nd to 1400 ng/g) and $\sum_{7}$PCBs (0.74-43 ng/g) were reported in soils from the Kingtom WEEE dumpsite in Freetown, Sierra Leone. The concentrations of PBDEs in these two locations were reported to exceed the background concentrations from Tanzania and

Kenya. Sources were associated with the burning of WEEE and/or the incorporation of waste particles in the soil. Here, BDE-209 was reported as the predominant congener with concentrations ranging from 1.2-100 ng/g[23].

In Nigeria, Ohajinwa *et al.* reported concentrations of $\sum_{17}$BDEs (median = 0.0032-21 ng/g) for informal WEEE recycling locations in Ibadan, Lagos and Aba in 2019[32]. These concentrations were reported to be higher at the burning sites than at the dismantling sites, and the concentrations from the two sites exceeded those of the other locations studied. BDE-209 was reported as the predominant congener with 18 ng/g (upper bound concentration). Conversely, in a subsequent 2020 study[33] from Benin City, Nigeria, the authors reported only BDE-47 above the detection limit in the concentration range of nd to 1.90 ng/g from the PBDE congeners investigated (BDEs 47, 79, 99, 153 and 209). The sources were attributed to the burning and leaching of PBDEs from WEEE plastics into the soil.

Olutona *et al.* reported concentrations of six individual PBDE congeners (BDEs 28, 47, 99, 100, 153, and 154) in soils sampled from Obafemi Awolowo University's dumpsite, Ile-Ife, Nigeria, with BDE-153 being the dominant BDE congener (14 ng/g)[34]. Higher concentrations of PBDEs were reportedly found in the top layer of soil than in the layers of soil below, indicating either atmospheric deposition or upward mobility of PBDEs in soils to enrich the top layer. Oloruntoba *et al.* reported excess concentrations of $\sum_{7}$BDEs (110-370 ng/g) in soil samples collected from Karmo and Anjanta dumpsites in Abuja, Nigeria[35]. These concentrations were reported to significantly exceed the control sites. The authors considered these high concentrations as possible reasons for the high levels of PBDEs reported in eggs and vegetation around the same dumpsites[36], suggesting the potential transfer of PBDEs from contaminated soil into the food chain. PBDE concentrations were reported to be higher in the wet season (June) compared to the dry season (March), associated with a high "wash out" of atmospheric PBDEs in the wet season.

Oketola and Akpotu[37] reported $\sum_{6}$PCBs (3-410 ng/g) in soils from seven dumpsites located in Lagos and Ibadan, Nigeria. This study indicated higher concentrations of PCBs in samples collected within Lagos, which is a more industrial and populated location. Meanwhile, lower $\sum_{15}$PCBs concentrations (24-29 ng/g) were reported in soil collected from Afe Babalola University's dumpsites in Ado-Ekiti, Nigeria, = by Adesina[27]. Ouabo *et al.* reported 32-73 ng/g for $\sum_{30}$PCBs in soil samples from abandoned WEEE sites in Douala, Cameroun[38]. In this study, PCB-52 was reported as the dominant congener (0.43-7.4 ng/g). Relatively high concentrations for $\sum_{18}$PCBs (1000-4900 ng/g) were reported by Debela *et al.* from soil samples collected from an old transformer dumpsite in Addis Ababa, Ethiopia[39]. The dominant congener was again reported as PCB-52 (mean = 360 ng/g).

Akortia *et al.* reported $\sum_{7}$BDEs (7.1-11 ng/g) from landfill soil samples collected from sites in Gauteng Province, South Africa, with BDE-183 the predominant congener[40]. Sources were related to consumer goods and abrasions of materials containing PBDEs within the landfill. The authors reported higher concentrations of PBDEs within the coarse soil fraction (150-250 μm) compared to a finer fraction (45-150 μm). In Dar es Salaam, Tanzania, Nipen *et al.* reported concentrations of SCCPs and MCCPs as 11-5300 and 26-5100 ng/g, respectively[13]. The concentrations from the municipal waste dumpsite and that of the WEEE sites were specifically reported to exceed all other studied locations. Compared to this study and the one by Möckel *et al.*, Nipen *et al.* attributed higher MCCP/SCCP ratios in their data to a higher volume of WEEE processed in Ghana, cruder processing methods used for WEEE dismantling/recycling, differing socioeconomic development in Tanzania and/or the later year of study, during which time the use of modern electronics could potentially contain greater quantities of MCCPs than SCCPs due to international policy shift from SCCPs to MCCPs use in these products[13,23].

Concentrations reported in sediment and leachate from landfills and dumpsites

Five studies were identified to target landfill/dumpsite sediments, while nine were found for leachates [Table 1]. All of these documents originated from South Africa. Olukunle and Okonkwo[41] reported $\sum_3$AFRs (EHTBB, BEHTBP and BTBPE) (mean = 71 ng/g) and HBCDD (mean = 33 ng/g) in selected landfill sediments from Gauteng Province, South Africa. In leachates, HBCDD and $\sum_3$AFRs concentrations were reported as 0.14 and 0.072 ng/L, respectively. The authors reported detection of most AFRs in samples of unlined/unprotected landfill, while HBCDD was mostly detected in samples of lined/protected landfills equipped with incinerators. According to the authors, this study was the first to confirm the presence of AFRs and HBCDD in municipal solid waste landfills in South Africa.

Sibiya *et al.* observed PBDE concentrations ($\sum_9$BDEs 2.5-4.9 ng/g and 0.32-1.4 ng/L in sediment and leachate, respectively) from seven functional landfill sites in Johannesburg and Pretoria, South Africa[42]. These concentrations were reported to be higher in landfills that were lined/protected with geomembrane liners. One landfill site (Hatherly) without geomembrane liners reported high concentrations of PBDEs ($\sum_9$BDEs 0.045-0.15 ng/L) in groundwater beneath the unlined landfill site, indicating possible migration of PBDEs to the surrounding groundwater. However, higher concentrations of $\sum_9$BDEs (0.29-0.449 ng/L) were reported when monitoring groundwater around a lined landfill (Marie Louis). The authors attributed these differences in concentrations to the size or incompleteness of the geomembrane liner, age or possible degradation/damage of the liners and/or contamination from improper disposal from nearby industries. BDE-209 was reported as the dominant PBDE congener in both landfill leachates (0.14-0.47 ng/L) and landfill sediments (1.2-3.0 ng/g).

Further South African studies from Johannesburg and Pretoria by Sibiya *et al.* indicated $\sum_{10}$OPFRs (120-1660 ng/g), $\sum_5$BDEs (0.82-1.4 ng/g) and $\sum_7$PCBs (2.3-6.9 ng/g) from landfill sediment samples and $\sum_{10}$ OPFRs (560-17,000 ng/L) from landfill leachate samples[43]. The high concentrations of OPFRs compared to the relatively low concentrations of PBDEs and PCBs were attributed to the possible replacement of PBDEs and PCBs by OPFRs in consumer products imported into South Africa. The initial 2010 investigation on Pretoria's landfill sediment by Odusanya *et al.* reported $\sum_{15}$BDEs (33 ng/g). In this report, BDE-209 was reported below the limit of detection, attributed to photolytic degradation of samples[44]. Daso *et al.* reported concentrations of nd to 50 ng/L γ-HBCDD, not detected for tetrabromobisphenol A (TBBPA) and 40-480 ng/L for $\sum_5$BDEs in landfill leachates collected from sites in Johannesburg and Pretoria (Gauteng Province)[45]. Similar to the study by Odusanya *et al.*, BDE-209 was reported as not detected[44]. α-HBCDD and β-HBCDD were also reported below the limit of detection. The authors attributed the non-detection of α- and β-HBCDD to the low composition of α-HBCDD (10%-13%) and β-HBCDD(1%-12%) in the HBCDD technical mixture, as well as the extremely low water solubility of γ-HBCDD (2.1 μg/L) together with its affinity for suspended solids in aqueous media. The authors suggested consideration of the distinctive physicochemical parameters of TBBPA when developing the chromatographic methods for its quantification by LC-TOF-MS/MS, a factor they believed could affect the detection of TBBPA.

Daso *et al.* in Cape Town, South Africa, reported a PBDE concentration range for $\sum_8$BDEs (0.28-2200 ng/g) for Bellville, Coastal Park and Vissershok landfills[46]. The authors attributed the PBDE concentrations to the huge volume of wastes deposited into the landfills, frequency of precipitation, generally hot climate, degree of waste compaction and age of the landfill sites. PBDE sources at Coastal Park and Vissershok landfills were largely attributed to the nearby wastewater treatment plant (WWTP)-derived sludge. However, multivariate analysis revealed multiple sources for PBDEs. The authors suggested that the observed differences in the PBDE levels between the Vissershok (0.28-21 ng/L) and Coastal Park landfills (1.7-1200 ng/L) could be due to the differences in sampling method employed during leachate collections, with organic matter from bottom sediments influencing the availability of the contaminants.

Odusanya *et al.* reported $\sum_{13}$BDEs (8.4-55 ng/L) from leachates collected from Soshanguve, Temba, Garankuwa, Hatherley and Kwaggasrand landfills, South Africa[47]. The lowest PBDE concentration was reported in Kwaggasrand, which was considered the youngest landfill (seven years old). PBDE congeners BDE 28, 47, 71 and 77 were detected in leachate samples from all landfill sites; all congeners were reported in two of the oldest landfill sites (both ten years old). The authors reported that higher levels of organic materials may have significantly contributed to elevated PBDE concentrations in leachate.

Olukunle *et al.* reported PBDE concentrations for the $\sum_{7}$BDE for sediment (0.8-8.4 ng/g) and leachate (0.13-3.7 ng/L) in samples collected from landfills in Gauteng, South Africa[48]. BDE-209 (mean = 1.6 ng/g) was reported as the dominant congener in the majority of sediment samples. The highest concentrations of $\sum_{7}$BDEs were reported in geomembrane-lined landfills. The authors observed a possible positive relationship between trace metal concentrations and PBDE concentrations in leachate samples. Ololade *et al.* reported concentrations of $\sum_{14}$PCBs (3.0-41 ng/L) in leachate samples collected from Lagos (Olusosun) and two other dumpsites at Ondo (dumpsite of Ondo State Waste Management Authority) and Ikare-Akoko[49]. These dumpsites were reported not to have any protective liner. Higher concentrations were reported in Olusosun compared to the other landfills studied, with factors of population density, age of dumpsite, quantity and nature of deposited wastes and higher market density attributed to these differences. Concentrations of $\sum_{14}$PCBs (nd to 67 ng/L) [Table 2] were reported in the groundwater samples around these dumpsites, suggesting percolation of PCBs into local groundwater. Ibor *et al.* reported $\sum_{8}$PFASs in stimulated leachate from Lenna solid waste dumpsite, Calabar, Nigeria[50]. The highest PFAS detected was reported as perfluorodecanoic acid (PFDA) (5.0 ng/g), while the lowest detected PFAS was perfluorobutane sulfonic acid (PFBS) (0.05 ng/g).

Concentrations reported in human/biological samples, indoor dust and groundwater from landfills and dumpsites

A summary of the concentrations reported on human/biological samples is presented in Table 2, while the details of individual compounds are shown in Supplementary Tables 2-6. In two studies conducted in 2019 and 2021, high levels of PBDEs were reported from selected plants ($\sum_{7}$BDEs 8.5-61 ng/g dw)[35], free-range eggs ($\sum_{7}$BDEs 190-370 ng/g lipid wt.)[50] and cow milk samples ($\sum_{7}$BDEs 33-100 ng/g lipid wt.)[50] collected from Karmo and Anjanta dumpsites, Abuja, Nigeria. Oloruntoba *et al.* reported that these concentrations significantly exceeded those of the control samples[35,36]. $\sum_{7}$BDEs were reported to vary between plant roots (25-61 ng/g dw) and shoots (8.5-32.2 ng/g dw)[35]. In the egg samples, BDEs 47, 99, 100 and 153 were reported as the predominant congeners in egg samples, while BDEs 47 and 99 were the dominant ones in milk samples. The authors attributed the difference to metabolism and debromination of higher-brominated PBDEs during transfer into milk. Oloruntoba *et al.* provided evidence of dietary transfer of contaminants from dumpsites to humans through contaminated vegetable, egg and dairy consumption[35,36]. While contamination of dumpsite soil and plants was directly associated with waste disposal and open burning of deposited wastes, the authors associated the relatively lower contamination of the control soil and plants with air pollution and atmospheric deposition.

High concentrations of PBDEs (770-1300 ng/g lipid wt.), TBBPA (< 4.2-150 ng/g lipid wt.), SCCPs (310-2100 ng/g lipid wt.), ICES indicator $\sum_{7}$PCBs (290-620 ng/g lipid wt.) and $\sum_{3}$AFRs (41-57 ng/g lipid wt.) were reported in free-range eggs collected around Agbogbloshie WEEE dumpsite, Ghana[51]. These concentrations were related to high informal activities and processes in the WEEE scrapyard. The concentrations of PCBs, PBDEs and SCCPs reported in Ghanaian free-range eggs[51] generally exceeded similar reports on free-range eggs collected from Yaoundé, Cameroon's dumpsite (PCBs: 28-36 ng/g lipid wt., SCCPs 150 ng/g lipid wt. and BDEs 0.2-2.8 ng/g lipid wt.). A similar investigation from Mbeubeuss dumpsite in Dakar, Senegal, by IPEN[52] indicated contamination by $\sum_{7}$PCBs (29 ng/g lipid wt.)

Table 2. Summary of the reports on samples around landfills/dumpsites (concentrations in ng/L for leachate or water and ng/g for soil, dust or human/biological samples)

Human/Biological samples collected around landfills/dumpsites					
Abuja, Nigeria	ns (n = 56)	[f]Eggs	- $\sum_7$BDEs	[l]190-370	[36]
			-	[l]33-100	
		Cow milk			
Accra, Ghana	ns (n = 2)	[f]Eggs	- $\sum_7$PCBs	[i]290-620	[51]
			- ∑BDEs	770-1300	
			- TBBPA	< 4.2-150	
			- Chlorinated paraffins (SCCPs)	310-2100	
			- $\sum_3$AFRs	41-57	
Yaoundé, Cameroon	2018 (n = 3)	[f]Eggs	- [i]$\sum_7$PCBs	[l]28-36	
			- Chlorinated paraffins (SCCPs)	[l]150	
			- ∑BDEs	[l]0.5-2.8	
Accra, Ghana	2011 (n = 39)	Human blood samples	- $\sum_3$PCBs	[a]82	[54]
Accra, Ghana	2015 (n = 88)	Human blood plasma	- $\sum_6$PCBs	340 (30-15,000)	[55]
Accra, Ghana	2014 -2016 (n = 105)	Human breast milk	- $\sum_6$PCBs	[l]4.4	[53]
Dakar, Senegal	ns (ns)	[f]Eggs	- [i]$\sum_7$PCBs	[l]29	[52]
Abuja, Nigeria	ns (n = 40)	Plants	- $\sum_7$BDEs	8.5 - 61	[35]
Indoor dust					
Durban, South Africa	2012 - 2013 (n = 3)	Indoor dust	- $\sum_8$BDEs	2,600-44,000	[56]
Durban, South Africa	2012-2013 (n = 3)	Indoor dust	- $\sum_3$PCBs	54-490	[56]
Groundwater around landfills/dumpsites					
Gauteng Province, South Africa	2014 (ns)	Monitoring groundwater	- $\sum_9$BDEs	0.045-0.15	[42]
Lagos & Akure, Nigeria	ns (ns)	Groundwater	- $\sum_{14}$PCBs	nd-67	[49]

[l]Lipid wt (ng/g); [f]free range chicken eggs around dumpsite; nd: non detect; [a]reported as µg/L and converted to ng/L; ns; not specified; [i]ICES indicator PCBs.

in free-range eggs.

Asamoah *et al.* reported mean concentrations of 4.4 ng/g lipid wt. for $\sum_6$PCBs from the milk of volunteer mothers in the hotspot of Agbogbloshie WEEE dumpsite, Ghana[53]. This concentration was reported to significantly exceed the concentration (0.03 ng/g lipid wt) of samples from "non-hotspot" areas, with the predominant PCB congener reported as PCB-28 [mean = 1.3 ng/g (lipid weight)]. From the same Agbogbloshie WEEE dumpsite, Wittsiepe *et al.* reported a concentration of 82 ng/L for PCB congeners 138, 153 and 180 in workers from the WEEE scrapyard and the control sites[54]. Interestingly, and perhaps counterintuitively, the concentrations reported from the control group were significantly higher than those of the Agbogbloshie scrapyard workers. The authors reported that WEEE-related activities had no influence on internal exposure and called for further investigation of their observation of higher PCB exposure for people living in areas not associated with WEEE activities.

Kaifie *et al.* reported PCB concentrations of 340 ng/L (mean) for $\sum_6$PCBs in human blood plasma from WEEE recycling workers at Agbogbloshie, Ghana[55]. All target PCB congeners were reported in the plasma of the WEEE site workers in this study. In contrast to Wittsiepe *et al.*, the authors reported a significant difference for lower chlorinated PCBs (PCBs 28, 52 and 101) when compared with the control group[54]. According to Kaifie *et al.*, the PCB congeners 138, 153 and 180 monitored by Wittsiepe *et al.* are associated with food ingestion, which is age or time related, in addition to occupational exposure[54,55]. Lower PCB congeners were regarded as accurate markers to differentiate between environmental exposure and occupational exposure as a result of their shorter half-lives since they are not confounded by age or dietary habits. Kaifie *et al.* reported dismantlers and burners to have the highest value of occupational related PCBs 28 and 52[55].

Abafe and Martincigh[56] reported high concentrations of $\sum_8$BDEs (2600-44,000 ng/g) and $\sum_3$PCBs (54-490 ng/g) in the indoor dust samples collected around WEEE recycling locations in South Africa. Higher PBDE concentrations were reported around sampling points characterised by WEEE polymers compared to locations characterised by internal components of personal computers, mobile phones and fridges. BDE-99 and BDE-209 were reported as the most prevalent congeners, while PCB-180 was reported as the dominant PCB congener. Concentrations of both PBDEs and PCBs in dust were reported to reduce after the clean-up of the WEEE recycling site.

Concentrations of target contaminants reported in African wastewater and wastewater treatment sludge

In total, eight documents were found on African wastewater and wastewater treatment sludge. The concentrations obtained are summarised in Table 3, while the details of the individual compounds are presented in Supplementary Tables 2-6. Sindiku *et al.* reported low $\sum_{10}$PFASs (0.10-0.54) ng/g in sludge samples collected from hospital, industrial and domestic WWTPs, in Lagos, Oyo and Ogun, Nigeria[57]. Perfluoroalkyl carboxylates having carbon chain with ≥ 8 fluorinated carbons were reported at higher levels than those with < 8 fluorinated carbons. The authors reported that PFAS concentrations were lower compared to other regions in the world. No point sources were attributed by the authors. The low concentration of PFASs from municipal sewage plants was related to low PFAS uses in Nigerian residential settings. The highest concentration of PFAS detected, perfluorooctane sulfonate (PFOS) (0.54 ng/g) reported in hospital sewage sludge, was attributed to minor releases from medical equipment.

Chirikona *et al.* reported concentrations of PFOS (0.9-9.8 ng/L) and PFOA (1.3-28 ng/L) for wastewater samples and PFOS (0.10-0.68 ng/g) and PFOA (0.12-0.67 ng/g) for sludge samples collected from hospital, domestic and industrial WWTPs in Kenya[58]. Similar to the study by Sindiku *et al.* all samples indicated PFASs, but higher concentrations were reported in domestic WWTPs[57].

Daso *et al.* reported $\sum_8$BDEs in sewage sludge (13-650 ng/g), raw water (370-4400 ng/L), secondary effluent (19-2600 ng/L) and final effluent samples (90-15,000 ng/L) collected from WWTPs in Cape Town, South Africa[59]. The PBDE sources were attributed to general wear and tear of contaminated home products such as furniture and other textile materials that could be transferred to the sewer system through washing and floor mopping. The authors highlighted the reuse of treated effluents as a source of PBDEs in the South African environment, particularly when used for agricultural purposes, where transfer of contaminants into the food chain may occur.

Another study from Cape Town (Potsdam, Cape Flats and Bellvill), South Africa, by Fatoki *et al.* revealed $\sum_8$BDEs (0.18-4300 ng/g) in sewage sludge[60]. The variation in concentrations was associated with the time period sampled, the composition of wastewater reaching the WWTPs and changes in lifestyles of the local

Table 3. Summary of the reports on wastewater (concentrations in ng/L for water and ng/g for sludge)

Location	Sample number (Study period)	Environmental media	Treatment type	Chemicals	Concentrations-mean (range)	References
Wastewater sludge						
Lagos, Oyo and Ogun, Nigeria	2012	Sewage sludge	Activation/aeration	$\sum_{10}$PFAS	0.27 (0.01-0.54)	[57]
(Bungoma, Busia, Kakamega, Kisumu, Kisii, and Mumia), Kenya	2013 (*n* = 9)	Sewage sludge	Aerated lagoon	$\sum_{9}$PFAS	*0.17 (0.12-0.67) **0.44 (0.10-0.68)	[58]
Cape Town, South Africa	2010-2011 (*n* = 9)	Sludge	Membrane Bioreactor System	$\sum_{8}$BDEs	13-650	[59]
Alexandria, Egypt	2010-2011 (ns)	Waste sludge	Activated sludge process	$\sum_{7}$PCBs	[i]5600-11,000	[61]
Cape town, South Africa	2010-2011 (ns)	Sludge (within)	Activated sludge system & bioreactor system	$\sum_{8}$BDEs	0.18-4,300	[60]
Wastewater						
(Bungoma, Busia, Kakamega, Kisumu, Kisii, and Mumia), Kenya	2013 (*n* = 9)	Wastewater	Aerated lagoon	$\sum_{9}$PFAS	*12 (1.3- 28) **4.0 (0.9-9.8)	[58]
Kampala, Uganda	2015 (*n* = 4)	Wastewater	sedimentation and a secondary/biological treatment using trickling filters	$\sum_{10}$PFAS	[#]4.5 (3.4-5.1) [##]7.7 (5.6-9.1)	[62]
Gauteng Province, South Africa,	2016 -2017 (ns)	Wastewater	Primary settling tank; secondary settling tank & external nitrification	$\sum_{7}$PFAS	[#]630 [##]220	[63]
			Anaerobic pond & biological filter		[#]130 [##]77	
			Activated sludge process		[#]200 [##]36	
Cape Town, South Africa	2010-2011 (*n* = 18)	Raw water	Membrane Bioreactor System	$\sum_{8}$BDEs	370-4400	[59]
		2nd effluent from WWTW			19-2600	
		Final effluent from WWTW			90-15,000	
Northeast Tunisia, Tunisia	ns (ns)	Textile wastewater	-	$\sum_{7}$PCBs	[i]280,000-1,200,000	[64]
Ramadan city, Egypt	2008-2009 (ns)	Raw wastewater	-	$\sum_{12}$PCBs	27,000 (12,000-52,000)	[65]
		Primary sedimentation effluent	-	$\sum_{12}$PCBs	18,000 (10,000-22,000)	
		Final effluent	Aerated oxidation	$\sum_{12}$PCBs	8,200 (5600-11,000)	

*PFOA; **PFOS; [i]ICES indicator PCBs; [#]influent; nd: non detect; ns: not specified; [##]effluent.

residents. Similar to the study by Daso *et al.*, the authors attributed the sources of the PBDEs to home products - particularly of second-hand value, such as furniture, electrical and electronic equipment, carpets and upholstery where the contaminants have the possibility of entering the sewer system through floor cleaning and subsequent leaching[59]. Other attributed sources were associated with industrial-related sources, such as heavy-duty machines, vehicular activities and mismanagement of municipal solid wastes. Most of the congeners were reported to be found to accumulate in the secondary sludge; for this reason, the authors believed that finely suspended particles could be an important mechanism for the removal of PBDEs from aqueous media.

Barakat *et al.* reported excessive concentrations of ICES $\sum_7$PCBs (5600-11,000 ng/g) in sewage sludge samples collected from Alexandria, Egypt[61]. The highest concentration was reported in the anaerobically digested sample (ADS). These high concentrations were associated with the concentration effect of the dewatering process of WWTP and the persistence of PCBs. For wastewater, Dalahmeh *et al.* reported concentrations of $\sum_{10}$PFAS in influent (3.4-5.1 ng/L) and effluent (5.6-9.1 ng/L) from Bugolobi WWTP, Uganda[62]. The higher concentrations of PFAS in the effluent were associated with inefficient removal of PFAS by the treatment processes of sedimentation (primary) and a biological treatment using trickling filters (secondary) within the WWTP. Much higher PFAS concentrations were reported in influents $\sum_{16}$PFAS (130-630 ng/L-range of means) and effluents $\sum_7$PFAS (77-220 ng/L-range of means) by Kibambe *et al.* from wastewater samples collected from Daspoort, Phola and Zeekoegat WWTPs, South Africa[63]. Similar to the report by Dalahmeh *et al.*, incomplete removal of PFAS was reported in all three WWTPs[62]. The removal efficiency was reported to vary among the three WWTPs; however, activated sludge recirculation was reported to perform better than biological filtration systems. According to the authors, the removal of PFAS in the WWTPs could be related to type and size of the three WWTPs; load of the PFAS discharged into the WWTPs; distinctive removal efficiencies of the WWTPs, which may depend on the design and operating factors such as temperature, mixed liquor suspended solids, sludge, hydraulic retention times; and feed flow rates in the biological tank.

For PCBs, Samia *et al.* observed excessive ICES indicator $\sum_7$PCBs (280,000-1,200,000 ng/L) in untreated textile wastewater samples collected at Oued El bey, Tunisia[64]. This discharge was reported to contaminate surface and groundwater, reaching concentrations of 90,000-470,000 and 5200-196,000 ng/L, respectively [Table 4]. Badawy *et al.* reported relatively lower concentrations for $\sum_{12}$PCBs (mean = 27,000 ng/L) from wastewater collected in 10th of Ramadan industrial city, Egypt[65]. PCB removal efficiency from the wastewater was reported as 74%, with a residual concentration of 8200 ng/L. The removal rate was reported as 11%-53% in the primary treatment but increased to 33%-74% in secondary treatment due to the degradation of PCBs by biological treatment. The most frequent and abundant PCB congeners were reported as PCBs 18 and 52.

Concentrations of target contaminants reported on contaminations from industrial/sewage waste

Five different studies were obtained that targeted our selected contaminants in industrially/sewage-polluted water. The concentrations from the reported studies are summarised in Table 4. On sites along the Vaal River, South Africa, Chokwe *et al.* reported concentration ranges for $\sum_5$BDE for water (90-260 ng/L), fish (4.63-33 ng/g lipid wt.) and sediment samples (10-24 ng/g ww); the HBCDD concentrations for water, fish and sediment samples were 510-1770 ng/L, 10-13 ng/g lipid wt. and 15-52 ng/g ww, respectively[66]. The highest of these concentrations were reported to be found in samples collected from effluents from the Rietspruit WWTP. In South Africa, a study by Groffen *et al.* on the Vaal River indicated $\sum_{15}$PFAS concentrations of nd to 39 ng/L from polluted water, nd to 209 ng/g lipid wt for fish and not detected for sediment, with the exception of PFOS [2.36 ng/g dry weight (dw)] detected at Thabela Thabeng[67].

Olutona *et al.* reported concentrations of $\sum_6$BDEs (30-450 ng/L) in water samples collected from Asunle River, an adjoining stream of the Obafemi Awolowo University dumpsite, Nigeria[68]. These concentrations were reported to decrease downstream with a possible dilution effect resulting from increasing water volumes downriver. Subsequent reports on the river sediment[69] revealed concentrations of $\sum_6$BDEs (0.73-10 ng/g). BDE-153 was reported as having the highest concentration among all congeners in both water and sediment samples. The authors observed high concentrations of the BDEs in June (wet season), attributed to the discharge of pollutants from the dumpsite during precipitation.

Table 4. Summary of the reports on industrially/sewage/dumpsite polluted water (concentrations in ng/L for water and ng/g for fish or invertebrates)

Location	(Study period) Sample number	Pollution source	Treatment type	Chemicals	Concentrations-mean (range)	References
Rivers						
Gauteng province, South Africa	2013 (*n* = 12)	WWTP effluent	-	$\sum_5$BDEs	90-260	[66]
				HBCDD	510-1770	
Gauteng province, South Africa	2014 (*n* = 9)	WWTP effluent	-	$\sum_{15}$PFAS	nd to 39	[67]
Northeast Tunisia, Tunisia	ns (*n* = 13)	Waste water	-	$\sum_7$PCBs	[i]90,000-470,000	[64]
Ile-Ife, Nigeria	2012-2013 (ns)	Dumpsite	-	$\sum_6$BDEs	30-450	[68]
Ile-Ife, Nigeria	2012-2013 (ns)	Dumpsites	-	$\sum_6$BDEs	0.73-10	[69]
Sediment						
Gauteng province, South Africa	2013 (*n* = 12)	WWTP effluent	-	$\sum_5$BDEs	[w]10-24	[66]
				HBCDD	[w]15-52	
Gauteng province, South Africa	2014 (ns)	WWTP effluent	-	$\sum_{15}$PFAS	[e]nd	[67]
Fish						
Gauteng province, South Africa	2013 (*n* = 12)	WWTP effluent	-	$\sum_5$BDEs	[l]15-33	[66]
				HBCDD	[l]10-13	
Gauteng province, South Africa	2014 (*n* = 33)	WWTP effluent	-	$\sum_{15}$PFAS	nd to 290	[67]
Groundwater						
Northeast Tunisia, Tunisia	ns (*n* = 13)	Polluted from waste water	-	$\sum_7$PCBs	[i]20,400 to 1,930,000	[64]

ns: not specified; [i]ICES indicator PCBs; [w]wet weight; [l]lipid weight; [e]except PFOS at Thabela Thabeng (2.4 ng/g).

Comparison of intra- and intercontinental data on African waste streams

The lack of similarity of the target compounds in most of the studies affects the ability to compare them. Comparisons made here are based on articles reporting similar chemical compounds. The range of ICES indicator PCBs (6.5-830 ng/g) reported by Moeckel *et al.* on Agbobgloshie's WEEE sites, Accra, Ghana, is higher than the similar reports (0.74-43 ng/g) on Kingtom e-waste samples (Freetown, Sierra Leone)[23]. These two concentrations far exceed the concentrations reported by Sibiya *et al.* (2.3-6.9 ng/g) on South Africa landfill sediment[43].

The upper limit of the concentration range (620 ng/g lipid wt.) of ICES indicator PCBs reported by Petrlik *et al.* for free-range eggs in Accra, Ghana's WEEE dumpsite exceeds the values (36 ng/g lipid wt.) reported for Yaoundé, Cameroon and Dakar, Senegal (29 ng/g lipid wt.)[51,52]. The total range of ICES PCBs indicator reported from three reports on dumpsite/WEEE recycling sites are within 0.74-83 ng/g (lipid wt.), while that of the free-range eggs sampled along dumpsite/WEEE sites are within 28-620 ng/g lipid wt.

The concentration range of HBCDD reported for South Africa's landfill leachate (mean = 0.024 ng/L) by Olukunle *et al.* is lower than the by Daso *et al.* (nd to 50 ng/L)[41,45]. The upper mean concentration of $\sum_8$BDEs reported by Daso *et al.*[46] (2200 ng/L) is over four times greater than the concentrations of the subsequent report of 480 ng/L[45].

On intercontinental comparison, the range of 50-120 pg/m^3 reported by Katima *et al.* [Table 1] for HBCDD in South Africa landfill air substantially exceeds the reported concentrations (< 0.05-6.1 pg/m^3) of Harrad *et al.* in Irish landfill air [Table 5][39,70]. The mean concentration of the individual BDEs 28, 47, 100, 99, 154, 153, 183 and 209 observed in Ghana's WEEE soil[23] [Supplementary Table 4] exceed the reports on Ireland, and particularly BDE-209 is 16 times greater than (mean = 1600 ng/g) the concentration reported for Ireland (upper limit = 100 ng/g).

The ICES PCB concentrations of 1300-3700 ng/g (range of means) reported by Arp *et al.* for Norway [Table 5] are considerably greater than those reported from Kingtom WEEE sites (mean = 4.7 ng/g) and Agbobgloshie's WEEE sites (mean = 92 ng/g)[23,71]. The upper concentrations of PCBs 28, 118, 138 and 153 in human milk samples collected from residents close to Vietnamese WEEE sites[72] [Table 5] exceed the concentrations reported for human milk samples collected from around Ghana's WEEE recycling sites [Supplementary Table 6], while concentrations of PCB-180 were similar for Vietnam (0.50-5.5 ng/g lipid wt.) and Ghana (nd to 6.0 ng/g lipid wt.)[53].

The $\sum_8$BDEs concentrations reported in wastewater from Cape Town, South Africa[59] [Supplementary Table 5] are 18 times higher than those reported in Harbin, China[73] [Table 5]. While BDE-209 is the common dominant congener, the reported concentrations by Cincinelli *et al.* (130-9000) from Italian sludge samples substantially exceed those reported by Daso *et al.* from South Africa (4.9-2300 ng/g)[59,74]. BDE-153, which is the dominant BDE congener (upper concentration = 97 ng/g lipid wt.) in egg samples collected from Nigerian landfill sites[36] [Supplementary Table 5], is ten times lower than reported concentrations from Chinese samples (1000 ng/g)[75] [Table 5].

Factors influencing releases of contaminants from African waste streams

Concentrations of the selected contaminant in African waste streams were reported to vary across locations, sampling periods[13,35,46,60], activities on dumpsites/landfill[32], waste treatment methods[25,61,62] and sometimes study methods including chromatographic methods[45] and sampling procedures[59]. Sources were specifically associated with the waste contents[13,43], which is directly related to the population's lifestyle[60]. Possibilities of escape of contaminants such as BDEs into subsoil were reported by Olutona *et al.* and Oloruntoba *et al.*, particularly for lower brominated congeners[35,36]. Contaminants of PBDEs and PCBs were reported in groundwater sources around landfills, heavily implying emissions from these sites[42,49].

From the reported studies, factors influencing releases or increasing levels of contaminants in African waste streams can be highlighted as the volume of waste relative to the capacity of landfill and/or WWTPs[60]; waste sources or types[63]; crude processing methods[13,32]; age of landfill, particularly as related to the effective phasing-out period of regulated contaminants[35]; potential degradation of heavier brominated congeners leading to volatilisation of lower brominated congeners[30]; volume, size or type of waste water plant treatment[63]; weak and/or damaged landfill liners or absence of landfill liners[42]; no or inadequate treatment procedure for collected landfill leachate; and lack of waste sorting or proper recycling processes[32,55].

Sibiya *et al.* and Olukunle *et al.* reported high contamination of PBDEs in landfill sediment samples. The elevated concentrations were attributed to landfill liners preventing percolation into groundwater systems[42,48]. Sibiya *et al.* reported comparatively lower BDE concentrations in older landfills (28 years old), with a suggestion that older landfills contain microorganisms that support the breakdown of contaminants and therefore limit concentrations[43]. Conversely, Oloruntoba *et al.* reported higher concentrations of $\sum_7$BDEs in a slightly older landfill (eight years old) compared to the youngest landfill site[35].

Table 5. Selected global reports on waste streams (concentrations in ng/L for leachate or water, ng/g for soil or dust and pg/m^3 for air)

Location	(Study period) Sample number	Environmental media	Chemicals	Concentrations-mean (range)	References
Republic of Ireland	2018-2019 (*n* = ns)	Landfill air	HBCDD	< 0.05-6.1	[70]
	2018-2019 (*n* = 14)	Landfill soil	HBCDD	< 0.015-6.2	
			BDE-47	0.0038-0.32	
			BDE-99	0.0074-0.44	
			BDE-153	< 0.013-0.94	
			BDE-183	< 0.013-7.3	
			BDE-209	10-100	
South-Eastern, Norway	2013-2014 (*n* = 31)	Soil from waste handling facilities	[i]∑7PCB	[#]1300-3700	[71]
Vietnam	2007 (*n* = 33)	Breast milk from women residing around WEEE sites	PCB-28	[l]0.42-34	[72]
			PCB-118	[l]1.0-13	
			PCB-138	[l]1.7-17	
			PCB-153	[l]1.7-16	
			PCB-180	[l]0.50-5.5	
Harbin, China	2012-2013 (*n* = 12)	Wastewater treatment plant	BDE-28	0.05-0.17	[73]
			BDE-47	nd to 0.70	
			BDE-99	nd to 0.87	
			BDE-100	nd to 0.21	
			BDE-153	nd to 0.59	
			BDE-154	nd to 0.16	
			BDE-183	nd-0.41	
			BDE-209	nd-240	
Italy	2009-2010 (*n* = 8)	Sewage sludge	BDE-28	(1.2) 0.4-2.9	[74]
			BDE-47	(11) 2.8-29	
			BDE-99	(17) 1.5-49	
			BDE-100	(3.8) 1.3-9.1	
			BDE-154	(3.4) 0.5-7.5	
			BDE-153	(4.7) 2.7-13	
			BDE-209	2700 (130-9000)	
South China	2010 (*n* = 41)	[l]Egg	BDE-28	[#]1.0-1.7	[75]
			BDE-47	[#]17-58	
			BDE-99	[#]2.8-5.5	
			BDE-100	[#]15-27	
			BDE-153	[#]16-1,000	
			BDE-154	[#]8.1-100	
			BDE-209	[#]1200-3700	

[#]Range of means; [i]ICES indicator PCBs; [l]ng/g (lipid wt).

Ohajinwa *et al.* reported that concentrations of targeted chemicals followed the order: burning sites > dismantling sites > repair sites > control sites[32]. High concentrations of BDEs found by Ohajinwa *et al.* were also attributed to the burning of WEEE[32]. Similarly, Tue *et al.* cited thermal debromination as a factor contributing to higher concentrations of lower brominated BDEs at open burning sites[31]. Debromination was suggested for higher BDE-28 concentration in WEEE recycling soil by Akortia *et al.*[30]. Odusanya *et al.* suggested photolytic properties for less than detectable observation of BDE-209[44]. However, Moeckel *et al.*

found no major association between burning and volatile PCBs[23].

Key possible factors influencing the concentration of organic contaminants in landfill were attributed to organic carbon contents. Akortia *et al.* and Sibiya *et al.* reported a significant correlation between PBDE concentrations and organic carbon[30,41]. However, only a weak correlation was observed between lower brominated BDE congeners and organic carbon by Daso *et al.*[45].

For seasonal sources, Katima *et al.* reported higher concentrations of HBCDD, PBDEs and AFRs in landfill air during summer months when compared to winter months[25]. This was associated with high temperatures in summer, which favour volatilisation emission rates of BFRs from wastes. Higher concentrations of PBDEs were reported in dumpsite soils during the June wet period by Oloruntoba *et al.* on dumpsite soil[35], suggesting a possible washout of atmospheric PBDEs[35]. Similar high June wet period concentrations were reported by Daso *et al.* for landfill leachate, and flooding effects were suggested as the possible influence[46]. However, Sibiya *et al.*[42] reported slightly higher PBDE concentrations in the winter (3.00-4.91 ng/g) compared to the summer (2.50-3.71 ng/g). The lower concentrations in the summer were attributed to an increase in precipitation rates leading to diluting effects of both leachate and sediments. Meanwhile, Barakat *et al.* observed no correlation between PCB concentrations and season due to the diffuse origins of PCB sources[60].

CURRENT WASTE MANAGEMENT, PRACTICES AND POLICIES TARGETING WASTES IN AFRICA

Increases in urban populations are closely associated with escalating waste production. Currently, Africa has the fastest urban population growth in the world, with urban populations estimated at 567 million people in 2015 and predicted to grow by an additional 950 million people between 2020 and 2050[76]. In 2012, a massive 125 million tonnes of municipal solid wastes (MSW) were generated within Africa and were predicted to rise to over 250 million tonnes by 2025[77]. Unfortunately, many African countries lack the infrastructural and human capacities to adequately cater to continuous increases in wastes[78]. Consequently, this has led to poor waste collections, averaging only 55% (68 million tonnes) of MSW and, subsequently, indiscriminate dumping and burning of wastes in the environment[79,80].

African countries are large parties to multilateral environmental agreements such as the Stockholm Convention of the United Nation Environment Programme, aiming for the eradication of hazardous chemicals in the environment[81], and the Basel Convention, which is in existence for the control of transboundary movements of hazardous wastes and their disposal[82]. In 1998, the Bamako Convention came into force in Africa in response to article 11 of the Basel Convention[83]. The aims of the Bamako Convention were to prohibit the importation of all hazardous wastes into Africa, minimise and control transboundary movements of hazardous wastes within Africa and ensure the disposal of wastes in an environmentally sound manner, among others[83]. These multilateral, regional and multi-national frameworks have substantially guided and supported environmental policies in Africa; however, interpretation and enforcement of these policies remain within the national jurisdiction of individual countries and are far too often undermined and poorly implemented.

While environmental policies exist in Africa, there is still a wide gap between environmental policies and actual implementation[77]. This is closely associated with Government financial and infrastructural limitations in combating increasing waste growth. Unfortunately, the growth of waste in Africa is complicated by the influx of consumer products, such as electrical and electronic equipment, mostly end-of-life goods, goods of second-hand value or cheap products with short lifespans to meet increasing urban

population growth. Although informal sectors seem to be playing some roles as private waste collectors and recyclers, their activities and effectiveness cannot be guaranteed due to the lack of appropriate monitoring.

Chemicals with characteristics of POPs have been classified as hazardous chemicals under Annex II of the Bamako Convention or Annex III of the Basel Convention (UN class = 9; code = H11/H12)[82,83]. Meanwhile, developed nations are recommending the complete destruction of POPs in waste containing POPs above the regulatory limits[27]. Unfortunately, for many African countries, information on regulatory standards for POPs in wastes is missing. Laboratories for POP evaluation are largely not available, bringing a level of doubt to the very limited recycling and disposal activities related to POP-contaminated waste. Capacities are limited for POPs waste treatment - including solvent base treatments and incineration, which require high energy consumption. Such high power and facilities are either not widely available or not economically viable for most African nations.

The present waste situation in Africa can be described as a burgeoning waste crisis that is projected to escalate rapidly within the near future. The resulting impact of this is the widespread contamination of the African environment and worsening health impacts due to increased exposure to these hazardous chemicals. Additionally, POPs, which are currently controlled in most developed countries, have the potential to be redistributed to Africa as a result of global distillation or grasshopper effects. Exclusive control of waste streams, particularly POP wastes, will require monitoring the progress of the current waste governance policies. There is also a significant need for improving local, national, regional and continual teamwork to combat waste. Importantly, infrastructural, human development and financial support will be required from developed countries.

CONCLUSIONS AND STRATEGY FOR FUTURE RESEARCH

The available studies reviewed here present evidence of substantial contaminations of PFAS, CPs, BFRs (including PBDEs, HBCDD and TBBPA), alternative flame retardants, PCBs and OPEs in African waste streams - dumpsites/landfills, sewage sludge, wastewater and industrial sewage-polluted waters. Different dominant congeners were reported, suggesting multiple influences on the sources of the waste streams. Concentrations of reported POPs and OPEs varied considerably throughout the collated research articles due to differences in sampling periods, sample methods, activities on dumpsites and waste treatment methods. Significant impacts due to the contamination of surface/groundwater, free-range eggs, vegetation and cow milk were evident in these studies. Lighter PCB congeners were reported as major means of exposure to workers around landfill/dumpsite/WEEE recycling sites. African data are comparable with (or in some cases exceed) global concentrations of the selected chemicals.

The articles on waste streams selected for this study were found from only 12 of 54 African nations, with the majority of articles originating from Ghana, Nigeria and South Africa, representing a high combined share of 78%. Studies were mostly focused on PBDEs and PCBs, a few studies were obtained for CPs, and PFAS were only targeted in wastewater/sludge. Only one study was obtained targeting OPEs from African waste streams, while no studies were found that included the POP mirex.

Information from this study suggested that African waste streams could possibly be neglected as primary/secondary sources of global persistent organic contaminants. In line with the information available from this study, the following research priorities are recommended:

1. Studies on OPEs and mirex in African waste streams are required. This will enable an analysis of the risks posed by these chemicals to the African continent.

2. Adequate management of waste streams will be relevant in addressing POPs and OPEs in Africa, in addition to support via workforce training and infrastructural development of waste streams.

3. Future strategies for research on African waste streams should include control studies to avoid misinterpretation of the influence of the sources from the waste streams.

4. Consistent choices of target chemical congeners are recommended for ready comparison across sites and between countries.

5. Long-term monitoring studies of individual contaminants in African waste streams and other environmental media are necessary to track action and progress made on waste and environmental legislation.

6. Education of the African public will be necessary to avoid and ease further negative POP and OPE waste impacts on the African environment and reduce adverse health effects on populations.

DECLARATIONS

Author's contribution

Draft of manuscript and collation of data: Akinrinade OE
Edited and proofed read the manuscript before submission for consideration for publication: Stubbings WA
All authors read and approved the final manuscript.

Available data and materials

Additional data are available in the Supplementary Materials.

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The authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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