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Status of brominated flame retardants, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons in air and indoor dust in AFRICA: A review

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ABSTRACT

While many African countries are signatories of the United Nations' Environment Programme (UNEP) Stockholm Convention aimed at eradication or reduction of persistent organic pollutants (POPs) in the environment, many such countries have limited financial and technical capacities to either combat the effects of POPs or effect their removal from the environment. Amongst those chemicals listed as POPs under the Stockholm Convention are polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and hexabromocyclododecane (HBCDD). Also of concern are polycyclic aromatic hydrocarbons (PAH), which are listed under the UN Economic Commission for Europe (UN-ECE)'s protocol on long range transboundary air pollution (LRTAP). This review examines the state of knowledge pertaining to concentration levels and trends of these contaminants in air (both indoor and outdoor) and indoor dust in Africa. Despite there being no known manufacture of PBDEs or HBCDD in Africa, concentrations in air of these contaminants in Africa are comparable to those in continents where the chemicals were initially produced and known to be widely used. Insufficient data were available to discern any temporal trend in concentrations of the target contaminants. However, the evidence highlights sources of PCBs, PBDEs, and HBCDD in Africa to include obsolete electrical and electronic equipment and informal handling and treatment of electronic waste. Elevated concentrations of PAHs in air and in indoor dust are evident. Concentrations of PAHs in indoor dust can be significantly influenced by outdoor sources, particularly vehicular emissions leading to higher concentrations in urban settings. With the current and projected increase in African urbanisation and demand for consumer goods, there is substantial potential for concentrations of PBDEs, HBCDD, PCBs, and PAHs to rise in the near future. There is therefore a need for long-term monitoring of concentrations of these chemicals in air and indoor dust at a range of locations across the African continent. This should be designed to assess spatial trends and human exposure via inhalation and incidental dust ingestion, as well as facilitating elucidation of temporal trends of POPs in Africa and evaluation of the impacts of measures to reduce concentrations.

1. Introduction

Persistent Organic Pollutants (POPs) are a group of chemical contaminants that are toxic, persistent in the environment, capable of bio-accumulation and undergoing long-range atmospheric transport. Included amongst those chemicals listed under the Stockholm Convention of the United Nations Environment Programme (UNEP) are brominated flame retardants (BFRs) like polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCDD), as well as polychlorinated biphenyls (PCBs). Related to this, while not listed under the Stockholm Convention, polycyclic aromatic hydrocarbons (PAHs) were in June 1998 one of 16 groups of chemicals listed under the United Nations Economic Commission for Europe (UN-ECE) Convention on Long Range Transboundary Air

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Pollution (LRTAP), that was signed by 33 countries and the European Commission.

BFRs are chemicals deliberately applied to many indoor consumer items such as upholstery, textile coatings, plastic products, wire and cable insulators and electronics casings to resist accidental combustion [2–4]. PBDEs and HBCDD are among the most commonly applied BFRs. The former were produced in three different major formulations specifically: Penta-, Octa- and Deca-BDE [5,6,8], which were applied as additives in different consumer products. For example, PentaBDE was primarily used in bedding and seating polyurethane foams, whereas OctaBDE and DecaBDE were primarily applied to electronics casings [9]. The PentaBDE mixture mainly comprises tetra- and penta-BDEs; the OctaBDE formulation mainly comprises hexa- and hepta-BDEs, while the commercial DecaBDE product contains mainly BDE-209 as well as small percentages of nona- and octa-BDEs [10]. HBCDD is mainly applied as an additive in polystyrene foam building insulation and was included among those POPs listed in Annex A of the Stockholm Convention with an exemption for use in expanded polystyrene and extruded polystyrene in buildings and a labelling caution throughout the lifecycle of such products. Both PBDEs and HBCDD were used in substantial quantities in the past. The historical production and consumption levels of commercial Penta-, Octa-, and Deca-BDE have been estimated to be ~175, 130, and 1600 kilotonnes respectively [12] and as at 2011, the global market demand for HBCDD was 31,000 tonnes *per annum* [13].

Polychlorinated biphenyls (PCBs) are a class of 209 individual congeners produced as technical mixtures under brand names such as Arochlor, Kanechlor, and Sovol [14]. Production of PCBs occurred mostly in the developed northern hemisphere and by the late 1970s was prohibited in most industrialised countries. Applications of PCBs included use as dielectric fluids in transformers and capacitors [15–17], as well as additives in: lubricating fluids, adhesives, building sealants, plasticisers, fire proofing agents, paints, and ink products [14], [18]. Current emissions of PCBs to the environment are a combination of primary emissions from remaining in-use sources such as old transformers, capacitors, and building sealants; primary emissions from paint, resin and pigments [18], [19], alongside secondary emissions (e.g. volatilisation from environmental surfaces like soil) as a legacy of past use [20,21].

While PBDEs, HBCDD, and PCBs all had intentional industrial/consumer applications, PAHs are mostly unintentionally generated from both natural and anthropogenic combustion-related activities. Anthropogenic activities comprising biomass burning and fossil fuel are significant sources particularly in urban spaces [22]. PAHs are mostly emitted as a mixture and have the possibility to transform into potentially more potent derivatives including oxygenated, nitrogenated, and hydroxylated-PAHs [23,24], though the parent PAHs are most frequently monitored. Many PAH are regarded as potential or known human carcinogens, with benzo[*a*]pyrene (BaP) noted in many studies and historically used as an indicator of the total PAHs mixture [25,26]. However, some studies include the toxicity potential of other PAHs, since PAHs are mainly generated in mixtures and the toxicity of a mixture of PAHs is often expressed as a BaP-equivalent (BaP_{eq}) [25,27]. The USEPA stipulates 16 PAHs to be monitored as a result of their toxicity and frequency of exposure in the environment [28]. In particular, 7 PAHs (benzo[*a*]anthracene, chrysene, benzo[*a*]pyrene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, dibenzo[*a,h*]anthracene and indeno[1,2,3-*cd*]pyrene) are considered potential or known carcinogens [29].

While environmental contamination with PBDEs, HBCDD, PCBs, and PAHs has been studied extensively in Asia, Europe, and North America; comparatively little is known about its extent and impacts in Africa. Given the large population of the African continent, this is an important omission. Although there has been little if any production within Africa of BFRs and PCBs, there is increasing concern that emissions of these contaminants in Africa may be substantial due to a variety of factors, such as: use of obsolete equipment like PCB-containing transformers [16], poor management of BFR and PCB-containing waste due to impaired economic and technical capability, importation of second hand goods containing regulated BFRs, along with possible long-range intercontinental transport of POPs from other industrialised regions [30]. The continuous use or presence of obsolete PCB-containing transformers is particularly noted in Nigeria [31].

Concentrations of PAHs in outdoor air are closely associated with urban areas, within which there are substantial PAH emissions due to the burning of fossil fuel as a result of industrial activity, traffic, and electricity generation. In Xu et al. [32], Africa is listed among the main contributors to the global PAHs budget. Moreover, weak implementation of environmental laws and consequent poor waste management, is thought to have led to extensive open waste dumping and combustion and concomitant emissions of PAHs in Africa [16].

In addition to concerns for the African population, increasing emissions of BFRs, PCBs, and PAHs in Africa make a potentially significant contribution to global emission inventories for these contaminants [34,35].

To date, numerous attempts have been made to characterise the presence in Africa of BFRs, PCBs and PAHs in several environmental compartments including soil, water, sediments, the atmosphere, and indoor dust with the overall aim of investigating the sources, levels and associated exposure risk to the local population [24,31,36–39]. Among these environmental compartments the atmosphere is particularly important, as its short mixing time means that it is a key vector for distributing contaminants over wide geographical areas beyond the location of original use/emission. Moreover, due to the high temperature experienced by most of the continent, volatilisation of POPs from both primary and secondary sources will be more facile, resulting in the atmosphere being a proportionally greater reservoir of POPs in Africa than in Europe or much of North America for example [20]. Outdoor air is considered a minor contributor to overall human exposure to POPs in developed regions like Europe and North America [40,41]. In contrast, the contribution of inhalation of outdoor air could be significantly higher in many developing economies in Africa due to higher concentrations as described above, coupled with behavioural factors such as people spending more time outdoors in hotter climates. In addition, greater emissions of POPs outdoors may arise in many parts of Africa due to a variety of factors, including: poor handling of waste materials, potential use of obsolete products (including transformers), and weak environmental laws (and enforcement thereof) leading to open waste dumping and burning of waste materials. Moreover, some studies have indicated that such outdoor sources can constitute substantial influences on contamination of indoor environments particularly with PAHs [42,43]. For indoor microenvironments, studies have indicated that in addition to air inhalation, contact with indoor dust likely represents a significant contributor to BFRs, PCBs, and PAHs [44,45].

Against this backdrop, it is clear that contamination of outdoor and indoor air as well as indoor dust in Africa is a pertinent issue. This paper thus examines current knowledge with specific reference to PBDEs, HBCDD, PCBs, and PAHs. It identifies areas of concern and research gaps.

2. Review methods

Data and information reviewed in this study were collected from peer-reviewed research articles searched from the Web of Science data base, Scopus, and Google Scholar with multiple

keywords, that is: “Brominated flame retardants” (or “BFRs”), “polybrominated diphenyl ethers” (or “PBDEs”), “polychlorinated biphenyls” (or “PCBs”), “polycyclic aromatic hydrocarbons” (or “PAHs”), “hexabromocyclododecane” (or “HBCD” or “HBCDD”), “Africa”, “indoor”, “dusts”, “outdoor”, “air”, “atmosphere”, and a list of African countries. Searches were applied within the time frame of 1st January 2000–31st December 2019. Articles were only accepted on the condition of peer reviewed and targeting BFRs, PAHs, PCBs, or HBCD in Africa atmosphere/air or indoor dust. In overall, 58 peer reviewed articles were selected for this study.

3. Results and discussion

3.1. Polychlorinated biphenyls (PCBs)

Tables 1 and 2 summarise data reported on concentrations of selected PCBs in studies of outdoor air, as well as indoor dust in Africa. Studies reporting concentrations of PCBs in indoor air from Africa were not found.

3.2. Concentrations in outdoor air

Pozo et al. [46,48] presented the first extensive report on POPs contamination of outdoor air in Africa as part of the long-term Global Atmospheric Passive Sampling (GAPS) network. Concentrations of Σ_{48}PCBs in Accra (Ghana) and De Aar (South Africa) were reported as < detection limit (dl) – 68 and < dl - 252 pg/m^3 respectively. Generally, relatively low concentrations in Africa were reported, as PCBs were only detected in two sampling periods and were not detected at the other two study locations in Malawi (Lilongwe) and South Africa (Kalahari). A related study [37], reported comparable concentrations at 3 locations in Durban, South Africa, with a mean of 128 ± 47 pg/m^3 $\sum_{82}$PCBs. Meanwhile, Klánová et al. [49] in the MONET_AFRICA sampling programme reported $\sum_7$PCBs concentrations (mean concentration ~ 833 pg/m^3 based on a passive air sampling rate of 4 m^3/day) in urban/industrial sites particularly Dakar, Senegal (North West Africa). Gioia et al. [20] reported $\sum_{29}$PCBs concentrations of ~300 pg/m^3 in Gambia and Ivory Coast. Lower concentrations were later reported in Mali ($\sum_6$ PCBs nd –52 pg/m^3, value - 14 pg/m^3) [50], northern Algeria (Dioxin like $\sum_{12}$ PCBs 14–66 pg/m^3) [51], and Bizerte, Tunisia ($\sum_{18}$PCBs in total solid particles (TSP) (0.7–4.0 pg/m^3) [53]. PCBs concentrations in outdoor air should vary substantially across Africa depending on location, season, influence of atmospheric transport from source regions, and proximity to specific local sources. This is reflected in the wide range of median concentrations (8–2074 pg/m^3) reported by Bogdal et al. [54] in Africa. Puzzlingly, while Garrison et al. [50] reported low concentrations in Bamako and Kati, Mali (Σ_6PCBs < dl – 52, mean = 14 pg/m^3) the highest Σ_7PCBs concentrations (2074 pg/m^3) detected in Africa by Bogdal et al. [54], were in Bamako, Mali. Concentrations in air as high as 280–4640 pg/m^3 (dl-PCBs: 3–389 pg/m^3) have been reported for Σ_{190}PCBs in Ghana [55], though Gioia et al. [20] had initially reported $\sum_{29}$PCBs to be present at concentrations of 8–24 pg/m^3.

Data available on atmospheric concentrations of PCBs in Africa are predominantly from short term studies, making it difficult to evaluate long-term trends. However, a possible increase in concentrations over time was reported in Uganda by Arinaitwe et al. [56], with $\sum_{105}$PCBs concentrations observed in Entebbe in 2003–2004 lower than measured at the same location between 2008 and 2010; although the authors recommended further monitoring to establish whether this increase was a sustained long-term trend. With respect to seasonal variations in concentrations of PCBs, Batterman et al. [37] observed higher $\sum_{82}$PCBs concentrations in winter than summer, the authors attributed this to meteorological factors particularly temperature inversions in winter and associated changes in boundary layer depth. In contrast, lower concentrations of $\sum_{12}$ dl - PCBs were reported in colder compared with warmer seasons by Moussaoui et al. [51] in Northern Algeria. The higher winter concentrations observed in Durban, South Africa by Batterman et al. [37] are of particular note, as studies in North America and Europe have previously reported PCBs concentrations in outdoor air to peak in summer, attributed to greater volatilisation of PCBs from surfaces and ventilation of contaminated indoor air at higher temperatures [57,58].

While comparison of atmospheric concentrations of PCBs between studies is hampered by the different sampling methods, years and seasons, as well as variation in the PCB congeners targeted in each study; some information may be gleaned from studies in which identical sampling and measurement protocols are employed at a range of locations, or at the same locations at different points in time. In the first year of the GAPS study (December 2004–December 2005), concentrations of Σ_{48}PCBs reported in Africa were relatively low and not detected in some samples from some locations. However, the 252 pg/m^3 recorded in De Aar, South Africa in one sample, exceeded most values observed in Europe, except Turkey (644 pg/m^3); and in Asia, except Kuwait (497 pg/m^3) and the Philippines (2826 pg/m^3) [48]. Highest Σ_7PCBs concentration (84 pg/m^3) was reported by Bogdal et al. [54] in their study of a large number of locations in 31 countries spread over Africa, Latin America, the Caribbean, and the Pacific Islands, to be in Mali, Africa. Moreover, the median concentration of 2.1 pg/m^3 $\sum_{18}$PCBs reported for Bizerte, Tunisia exceeded the 1.0 pg/m^3 reported for Marseille, France [53], while concentrations of Σ_{190}PCBs (280–4640 pg/m^3) measured in Ghana in 2010–2011 [55] exceeded those of Σ_{86}PCBs (6–1300 pg/m^3) recorded in Canada in 2007–2008 [59]. The authors of the Ghanaian study suggested the elevated concentrations detected could be at least partly attributable to emissions from informal e-waste treatment facilities. Likewise, the concentrations of $\sum_{29}$PCBs reported by Gioia et al. [20] in Ivory Coast (12–285 pg/m^3) and Gambia (74–297 pg/m^3) are comparable to those reported ($\sum_{28}$PCBs 28–897 pg/m^3) by Jamshidi et al. [60] in the UK but lower than concentrations ($\sum_{29}$PCBs 20–1700 pg/m^3) at various locations across Europe [61] and $\sum_{28}$PCBs (120–1080 pg/m^3) in India [62].

3.3. Concentrations in indoor settled dust

While no study was found that reported concentrations of PCBs in indoor air in Africa, a few data exist on PCB contamination of settled surface dust in indoor microenvironments in Africa [63]. reported the following median concentrations of Σ_3PCBs (PCBs 28, 153 and 180) in floor dust sampled from three micro-environment categories in South Africa: 724 ng/g (homes), 1040 ng/g (offices), and 1880 ng/g (computer laboratories). A further study from the same group in South Africa [64] revealed lower median concentrations of Σ_3PCBs in indoor dust collected from electronic waste recycling sites (54–490 ng/g) and ICT workshops (411 ng/g). Much lower median concentrations (29.3–98.4 ng/g) were reported by Harrad et al. [3] for Σ_6PCBs, in home, office, and automobile dusts collected from Lagos, Nigeria. However, Folarin et al. [31] observed higher median concentrations (21–2200 ng/g) of Σ_7PCBs in offices of Nigerian electricity generation facilities, attributing these higher concentrations to the presence of PCBs in insulating oil used in the electrical transformers at such sites. Similar concentrations were reported by Iwegbue et al. [65] (Σ_{28}PCBs 788–1095 ng/g, median concentrations) in three electronic workshops in Southern Nigeria.

Concentrations of PCBs in dust from South African [63] and Nigerian homes [3] substantially exceeded those in dust from

Table 1
Summary of concentrations of PCBs detected in outdoor air in Africa and in other illustrative studies.

Reference, Location		Mode of sample collection (Collection medium)	Sampling period (Sample number)	Sample Phase(s)	Concentration Range (pg/m^3)						
					PCB-28	PCB-52	PCB-101	PCB-138	PCB-153	PCB-180	Σ PCBs
[53] Bizerte, Tunisia		High volume sampler (QFF)	March 2015 –01/2016 (n = 11)	Particulate	0.002–0.2	0.007–0.3	<dl – 0.04	0.1–0.8	0.1–0.8	0.2–1.5	0.7–4.0 (2.1)[a]
[55] Ghana		Passive sampler (PUF)	May 2010 –07/2011 (n = 15)	Gaseous	NA	NA	NA	NA	NA	NA	280–4640[b]
[56]	Entebbe, Uganda	High volume sampler (PUF + GmF)	October 2008–07/2010 (n = 53)	Gaseous + Particulate	NA	NA	NA	NA	NA	NA	19.2 –244.0[c]
	Entebbe, Uganda		2003–2004 (n = 9)		NA	NA	NA	NA	NA	NA	27–186[c]
	Kakira, Uganda		1999–2000 (n = 19)		NA	NA	NA	NA	NA	NA	154–462[c]
	Kakira, Uganda		2003–2004 (n = 9)		NA	NA	NA	NA	NA	NA	26.7 –226.0[c]
[49]	Africa Continental Background	Passive sampler (PUF)	01-07/2008 (n = 156)	Gaseous	NA	NA	NA	NA	NA	NA	0.7–6.1[d]
	Rural and Agricultural Areas				NA	NA	NA	NA	NA	NA	0.7–25.6[d]
	Urban Background				NA	NA	NA	NA	NA	NA	1.2–20.3[d]
	Urban and industrial sites				NA	NA	NA	NA	NA	NA	1.0–133[d]
	Dumping Sites				NA	NA	NA	NA	NA	NA	3.0–34.7[d]
[20] (ICES PCBs - Sum of PCBs - 28, 52, 101, 118, 153, 138, and 180)	Gambia	Passive sampler (PUF)	05-07/2008 (n = 4)	Gaseous	*#1.4 –62.3	0.8–17.8	*0.9–8.3	0.9–6.2	**1.4–8.9	0.4–2.3	73.9–297.0 (30–125)[e]
	Ghana				*#1.6–3.0	0.8–2.1	*0.4–2.2	<dl - 2.3	**0.2–3.1	<dl –1.1	8.1–24.3 (3.1–11.8)[e]
	Ivory Coast				*#5.0–8.3	7.0–20.4	*4.2–10.4	4.9–20.3	**6.8 –31.9	1.7–6.5	12.3–285.1 (6–106)[e]
[51] Northern Algeria, Algeria		Passive sampler (PUF)	July 2008 –11/2009 (n = 12)	Gaseous	–	–	–	–	–	–	14.3–66[f]
[50] (Bamako and Kati), Mali		High volume sampler (PUF + GFF)	December 2001 and August 2008 (n = 49)	Gaseous + Particulate	–	–	0.1–18.0	0.01–12.7	0.01–12.5	–	<dl – 52 (14 ± 12)[g]
[37] Durban, South Africa		High volume sampler (PUF + QmF)	August 2004 –September 2005 (n = 110)	Gaseous + Particulate	–	1.4 ± 1.8	5.6 ± 4.2	##8.0 ± 2.9	**5.9 ± 2.0	0.4 ± 0.2	128 ± 46.8[h]
[46,48]	Accra, Ghana	Passive sampler (PUF)	December 2004	Gaseous	NA	NA	NA	NA	NA	NA	< dl – 68[i]
	De Aar, South Africa		–December 2005 (n = 3)		NA	NA	NA	NA	NA	NA	< dl - 252[i]
[54] East, South and West Africa		Passive sampler (PUF)	Not specified	Gaseous	NA	NA	NA	NA	NA	NA	8–2074 (177, 84)[j]
[53] Marseille, France		High volume sampler (QFF)	March 2015 –01/2016 (n = 11)	Particulate	<dl – 0.1	<dl – 0.2	0.1–0.3	0.1–0.5	0.1–0.5	0.1–0.5	0.5–2.7 (1.0)[a]
[60] Birmingham, UK		Passive sampler (PUF)	August 2003 –10/2004 (n = 11)	Gaseous	*#1.0–19 (6.1 ± 4.6)	0.4–33 (7.0 ± 6.8)	<dl – 44 (5.5 ± 7.9)	0.2–28 (2.9 ± 4.5)	0.2–33 (3.4 ± 5.4)	0.1–15 (2.0 ± 2.4)	27.6–897[K]
Jaward et al., 2004b Across Europe		Passive sampler (PUF)	06 - July 2002 (n = 71)	Gaseous	<5–230	1.6–210	*2.8–120	1.5–90	**1.9–110	<0.25–20	20-1700[l]
[62] India		Passive sampler (PUF)	07-09/2006 (n = 18)	Gaseous	31–175 (66 ± 55)	0.1–137 (27 ± 54)	# <dl – 116 (44 ± 43)	0.29–9.0 (2 ± 3)	0.5–3.0 (2 ± 1)	0.1–1 (1 ± 1)[m]	120–1080[n]
[59] Toronto, Canada		Passive sampler (PUF)	10/2007 –October 2008 (n = 19)	Gaseous	NA	NA	NA	NA	NA	NA	6–1300[o]

QFF – Quartz fibre filter, GmF – Glass microfibre filter, QmF – Quartz microfibre filter, PUF – Polyurethane foam, NA- Not Available, (-) Not investigated, dl - detection limit, * (+PCB 90), ** (+PCB 132), *# (+PCB 31), # (+PCB 99), ## (+PCB 163).

[a] Σ_{18} Range (median).
[b] Σ_{190} Range.
[c] Σ_{105} Range.
[d] Σ_{7} Range (ng/sample).
[e] Σ_{29} (Range).
[f] Σ_{12} Range.
[g] Σ_{6} Range (mean ± sdv).
[h] Σ_{82} (mean ± sdv).
[i] Σ_{48} (Range).
[j] Σ_{7} Range (mean, median).
[k] Σ_{28} Range.
[l] Σ_{29} (Range).
[m] Σ_{28} Range (mean ± sdv).
[n] Σ_{28} (Range).
[o] Σ_{86} PCBs (Range).

Table 2
Summary of concentrations of PCBs detected in indoor dust in Africa and in other illustrative studies.

Reference, Location	Sampling period (Sample number)	Microenvironment	Concentration (ng/g) – Range (mean, median)						
			PCB-28	PCB-52	PCB-101	PCB-138	PCB-153	PCB-180	Σ PCBs
[65]; Abraka and Warri, Nigeria	February-March 2019 (n = 10)	Computer, photocopier, and printer workshops	5.4–149 (55, 34)	3.2–39.5 (17.8, 18.3)	8.2–38.0 (23, 23)	<dl	126–566 (369, 392)	12.7–100 (40, 23)	97–2389 (974, 788)[a]
	February-March 2019 (n = 20)	Television, radio, stereo, and video player workshops	0.5–423 (112, 36)	4.2–158 (43, 27)	3.7–81.7 (36, 33)	14 - 14 (14, 14)	7.9–792 (440, 459)	13.9–73.6 (32, 24)	120–3949 (1379, 1095)[a]
	February-March 2019 (n = 10)	Telephone and tablet workshops	5.3–386 (108, 21)	6.8–154 (54, 28)	7.3–75 (30, 12)	<dl	160 - 425 (290, 289)	12.3–12.6 (12.5, 12.5)	740–1780 (1200, 1000)[a]
[31]; Lagos, Nigeria	June-December 2015 (n = 48)	Power Station Offices	<0.09–113 (22.4, 16.3)	<0.08–145 (23.4, 12.5)	<0.11–612 (38.3, 3.8)	2–973 (73.3, 24.9)	<0.11–740 (91.3, 8.9)	#<0.08–500 (92.4, 51.7)	21–2200[b]
[3]; Lagos, Nigeria	September-October 2014 (n = 12)	Homes	1.5–7.8 (3.8, 3.9)	0.8–8.6 (4.2, 4.5)	0.4–9.4 (2.7, 3.7)	0.3–22 (6.0, 75)	0.2–22 (5.8, 1.3)	#4.4–24 (10, 10)	NA
	September-October2014 (n = 18)	Offices	0.7–11 (5.2, 4.8)	0.5–11 (4.4, 4.6)	2.6–24 (6.2, 8.7)	2.3–26 (5.1, 7.3)	3.8–23 (6.5, 10)	#1.9–34 (14, 14)	NA
	/September-October2014 (n = 16)	Cars	0.2–4.0 (1.9, 1.9)	0.1–5.9 (2.1, 2.3)	0.1–5.5 (0.72, 1.3)	0.4–6.7 (1.4, 19)	0.1–9.1 (1.6, 2.5)	#0.5–5.7 (1.9, 2.3)	NA
[63]; Durban, South Africa	/August-October 2012 (n = 10)	Homes	16.1, 10.9	–	–	–	173, 150	702, 585	(891, 724)[c]
	August-October 2012 (n = 10)	Offices	64, 28	–	–	–	170, 136	689, 812	923, 1040[c]
	August-October 2012 (n = 11)	Computer laboratories	8.3, <dl	–	–	–	358, 62	1510, 307	1880, 360[c]
[64]; Durban, South Africa	Winter 2012 (n = 3)	ICT workshops	NA	–	–	–	NA	NA	411[c#]
	Winter 2012–2013 (n = 3)	Recycling centres	NA	–	–	–	NA	NA	54–490[c##]
[66] Kuwait	April 2011 (n = 15)	Homes	–	–	<0.2–835 (63 ± 210)	<0.1–435 (28 ± 109)	<0.2–310 (20 ± 77)	<0.1–105 (7 ± 26)	1–3080 (210 ± 770)[d]
Kuwait	April 2011 (n = 15)	Cars	–	–	<0.2–14 (1 ± 3.6)	<0.1–98 (0.8 ± 2.5)	<0.2–3.0 (0.4 ± 0.8)	<0.1–60 (0.7 ± 1.5)	0.6–26 (6.7 ± 9.1)[d]
Faisalabad, Pakistan	April 2011 (n = 15)	Homes	–	–	<0.2	<0.1–2.2 (0.5 ± 0.7)	<0.1–4.0 (0.8 ± 1.0)	<0.1–11 (1.2 ± 2.8)	1–38 (5.2 ± 9.2)[d]
Faisalabad, Pakistan	April 2011 (n = 15)	Cars	–	–	<0.2	<0.1–6.1 (1.1 ± 1.6)	<0.1–4.5 (0.9 ± 1.4)	<0.1–6.5 (0.7 ± 1.6)	0.7–30 (5.5 ± 7.5)[d]
[68] Hong Kong	(n = 20)	Offices	0.0–37 (7.8)	0.0–8.5 (1.9)	0.0–5.9 (1.1)	*1.3 – *33 (2.2)	1.1–45 (4.3)	0.0–22 (2.3)	52.5–589 (266)[e]
	(n = 6)	Electronic factories	0.0–6.2 (4.0)	0.0–2.1 (0.98)	0.0–2.0 (0.87)	1.3–3.4 (2.9)	0.0–18 (2.6)	0.0–5.2 (1.1)	47–249 (107)[e]
[67] Texas, US	October 2006 (n = 20)	Homes	**1.6–37 (9.5, 5.1)	1.7–28 (7.9, 6.2)	1.9–29 (10, 8.7)	1.1–31 (8.6, 6.5)	1–22 (8.4, 7.1)	0.7–20 (4.5, 2.6)	47–620 (220, 200)[f]
Birmingham, UK	July-August 2006 (n = 20)		**0.5–39 (6.3, 3.9)	0.3–53 (5.6, 1.8)	0.1–73 (6.1, 1.2)	0.1–50 (4.1, 1.1)	0.1–32 (3.3, 1.2)	0.1–8.1 (1.8, 0.89)	5.7–860 (110, 48)[f]
Toronto, Canada	January-March 2006 (n = 10)		**3.5–29 (10, 7.3)	3.4–37 (12, 7.2)	1.9–60 (15, 8.8)	1–49 (12, 9.5)	0.9–36 (11, 9.9)	0.5–24 (8.5, 6.8)	56–820 (290, 260)[f]
Wellington, New Zealand	September 2006 (n = 20)		**0.8–11 (3.3, 2.3)	0.4–13 (2.6, 1.4)	0.4–21 (3.1, 1.6)	0.3–11 (2.8, 1.8)	0.4–12 (2.7, 1.4)	<dl – 9.6 (2.3, 1.3)	11–260 (67, 46)[f]

* (+PCB 167), * (+PCB 31), # Range (mean, median), [a] Σ_{28} Range (mean, median), [b] Σ_{7} Range of median concentrations, [c]Σ_{3} (Mean, median), [c#] Σ_{3}, [##]Σ_{3} Range, Σ_{17} Range (mean ± sdv), [e] Σ_{37} Range (Median), Σ_{9}Range (mean, median).

Pakistani homes [66], but are comparable to those reported in dust from Kuwaiti homes (Table 1b). Moreover, median PCBs concentrations in house dust from South Africa [63] exceeded those reported in the US, UK, Canada, and New Zealand [67]. Likewise, PCBs concentrations reported in office dusts by Abafe and Martincigh [63] and Folarin et al. [31] exceeded those reported for commercial offices in Hong Kong [68]. In a similar vein, concentrations of PCBs detected in dust from electronic workshops in Nigeria and South Africa [63–65] exceed those reported for dust from electronic factories in Hong Kong [68]. Overall, the limited evidence available suggests concentrations of PCBs in indoor dust in Africa are comparable to those observed elsewhere in the world.

3.4. Potential factors influencing concentrations of PCBs in African air and indoor dust

Sources of atmospheric PCBs in Africa were attributed to local, regional, and global factors [20,37,56]. The influence of long range atmospheric transport was identified as comparatively low and most relevant for less chlorinated congeners [37]. Local and regional factors include emissions from obsolete equipment and facilities associated with historical PCB usage, such as electrical transformers [31], ships, and offshore gas platforms [50,54]. Other potential sources are PCB waste dumping as well as waste recycling facilities [20,37,55,64] and volatilisation from contaminated surface [56].

Overall investigation of the reported PCB congener profiles indicates the dominance of heavier PCB congeners, particularly PCB-153 and PCB-180, in indoor settled dust (Table 2). While it may be hypothesised that lighter, more volatile congeners, particularly PCB-28, should be dominant in outdoor air samples, available data are not sufficient for verification of this hypothesis (Table 1).

3.5. Polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCDD)

Similar to the situation for PCBs, there appear to be no published data on concentrations of PBDEs and HBCDD in indoor air in Africa.

3.6. Concentrations of PBDEs and HBCDD in outdoor air in Africa

The literature on concentrations in Africa of PBDEs and HBCDD in outdoor air and indoor dust is summarised in Tables 3 and 4, alongside illustrative data from other continents for comparison. The first information available is from the first year of the GAPs study, where Σ_3PBDEs (PBDEs − 47, 99, 100) were observed at the following concentrations at a number of African locations: Kalahari (South Africa) - < dl - 6 pg/m^3, De Aar (South Africa) - < dl - 4 pg/m^3, and Lilongwe (Malawi) - < dl - 4 pg/m^3. A further report based on samples collected in the GAPs study in 2014 [69], indicated comparable ΣPBDEs atmospheric concentrations in De Aar (South Africa) ranging between 0.1 and 1.1 pg/m^3. In Uganda, Arinaitwe et al. [36] reported median concentrations of Σ_{19}PBDEs (16.9 pg/m^3) and HBCDD (0.15 pg/m^3). The concentrations were found to increase between 2008 and 2010. Higher Σ_9PBDEs concentrations (100–2820 pg/m^3 (Σ_9PBDEs) and 12–117 pg/m^3 (HBCDD)) were reported by Katima et al. [70] in Gauteng Province, South Africa, with the highest concentrations recorded in the vicinity of landfill. Castro-Jiménez et al. [53] reported $\sum_{27}$ PBDEs in total solid particles (TSP) collected in Bizerte, Tunisia with concentrations in the range 1–54 pg/m^3 (median = ~6 pg/m^3).

The concentrations of BFRs detected in African outdoor air are generally comparable to those reported elsewhere. Data reported by Katima et al. [70] in South Africa (100–2820 pg Σ_9PBDEs/m^3) are similar to those recorded at 7 locations along a rural-urban transect in the West Midlands of the UK (122–1700 pg Σ_{13}PBDEs/m^3) [71], but exceed concentrations reported in Canada (0.47–110 pg Σ_{27}PBDEs/m^3) [59] and China (57–470 pg Σ_9PBDEs/m^3) [72]. These relatively high concentrations in South Africa are interesting as BDE-209 (often the most abundant PBDE) was measured in all four studies cited. Likewise, concentrations detected in Uganda (3–252 pg Σ_{19}PBDEs/m^3) in Arinaitwe et al. [36] were akin to those reported across Europe (1–250 pg Σ_8PBDEs/m^3) [61], while those of ΣHBCDD (<0.30–6.19, median – 0.15, pg/m^3) detected in Uganda (Arinaitwe et al. [36] were lower than the reported median concentrations (1.7–5.2 pg/m^3) for the Great Lakes [74]. However, levels of PBDEs reported in De Aar, South Africa (<dl – 4 pg ΣPBDEs/m^3) [48] were exceeded by those reported in the GAPS study at various locations in Canada and Europe [69]. Similarly, concentrations of HBCDD (12–117 pg/m^3) reported in South Africa by Katima et al. [70] were lower than those (3.5–410 pg/m^3) reported for the UK West Midlands [71] and for China (20–1800 pg/m^3) [72]. Moreover, Castro-Jiménez et al. [53] reported a slightly lower median concentration of Σ_{24}PBDEs in Bizerte, Tunisia (6 pg/m^3; range 1–54 pg/m^3) than in Marseille, France (9 pg/m^3; range 2.2–17.6 pg/m^3) in airborne particulates.

3.7. Concentrations of PBDEs and HBCDD in indoor dust

We found 11 peer reviewed publications reporting concentrations of PBDEs and HBCDD in indoor dust in Africa. Data from Nigeria and South Africa (Table 4) suggest concentrations of PBDEs in indoor dust vary between microenvironments in the order: recycling centres > computer laboratories > workshops > cars > offices > homes (Abafe and Martincigh, 2015 [63,64], 2016 [3,75,77]; Olukunle et al., 2015 [65,78,79]. Likewise, in Cairo, Egypt, median concentrations of PBDEs in dust followed the order: cars > workplaces > homes [80]. Across Africa, and in line with other locations, BDEs −47, 99, 100, and 209 appear the dominant congeners implicating the Penta- and Deca-BDE formulations as the principal sources.

Reports of concentrations of hexabromocyclododecane (HBCDD) in African indoor dust appear confined to Egypt (Cairo) and Nigeria (Lagos). Concentrations were substantially higher in Lagos than Cairo with a contrasting pattern observed in the two studies with respect to the relative concentrations in different microenvironments. Specifically, while Hassan and Shoeib [80] reported median concentrations of 6.2, 18.6 and 37.5 ng ∑HBCDD/g in homes, workplaces and cars in Egypt; higher concentrations of 394 ng/g (homes), 156 ng/g (offices) and 297 ng/g (cars) were reported in Lagos, Nigeria [7].

The median concentration of ∑PBDEs (1550 ng/g) in home dust reported in South Africa (Durban) [63] exceeds that detected in Australia (571 ng/g) [82] but is comparable to that recorded in Swedish homes (53–4000 ng/g) [83]. Lower concentrations were however reported in South Africa [77], Nigeria [3,78] and Egypt [80] (Table 4). Median concentrations of BDE-209 reported for all microenvironments in Ireland [41] exceeded those in Africa (Table 4). Concentrations of BDE-209 in dust from offices in Sweden [83] are comparable to reports in Egypt [80] but higher than those reported for South Africa [63,75] and Nigeria [3,78]. This observation was similar for the car dust. The median concentrations of ∑HBCDD reported by Abdallah et al. [7] in cars, homes, and offices in Lagos were lower than those reported in the same microenvironments in Ireland [41] but were comparable to those reported in Sweden [83] except that higher concentrations were observed in dust from Lagos cars. Meanwhile, concentrations of HBCDD reported in Egypt [80] and Nigeria [7] were exceeded by those reported in France [7].

Table 3
Summary of PBDEs and HBCDD concentrations in outdoor air from Africa and in other illustrative studies.

Reference, Location	Mode of sample collection (Collection medium)	Sampling period (Sample number)	Sample phase(s)	Concentration (pg/m^3) – Range (mean, median)									
				BDE-28	BDE-47	BDE-99	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209	Σ PBDEs	HBCDD
[70]; Gauteng, South Africa	Passive sampler (PUF)	May 2016 –January 2017 Winter (n = 8)	Gaseous	<dl – 124 (31, 0.01)	<dl – 212 (145, 183)	12 –410 (206, 201)	<dl – 94.1 (49, 50)	<dl – 97.4 (35, 22)	<dl – 103 (36, 20)	5.6–35 (20, 20)	83 –154 (108, 99)	100 –1041 (636, 702)[a]	31–70 (49.9, 49.5)
		Summer (n = 8)		<dl – 226 (57, 0.01)	3.31 –474 (138, 36.6)	90.6 –530 (236, 162)	5.13 –584 (155, 15)	<dl – 80.6 (24, 7)	<dl – 48.5 (15, 5)	5.8–50 (18, 8)	80 –240 (122, 84)	195 –2820 (910, 313)[a]	11.9 –117 (70, 75)
[53]; Bizerte, Tunisia	High volume sampler (QFF)	March 2015 –January 2016 (n = 11)	Particulate	<dl – 0.01	0.02 –0.5	0.03 –1.4	0.004 –0.5	<dl – 2.7	<dl – 0.9	<dl – 1.7	0.68 –13.3	1.0–54 (6.0)[b]	–
Rauert et al., 2018, De Aar, South Africa	Passive sampler (PUF)	January –December 2014 (n = 4)	Gaseous	0.052 –0.3	<2–0.3	<2	<0.6	<0.3	<0.2	<0.3	<1	0.091 –1.1[c]	–
Arinaitwe et al., 2014, Entebbe, Uganda	High volume sampler (PUF + GmF)	October 2008 –July 2010 (n = 56)	Gaseous + particulate	<0.4 –61 (2.9, 1.4)	<2.1 –50 (9.8, 7.0)	<1.7 –77 (4.4, 0.9)	<0.32 –4 (0.6, 0.3)	<0.12 –2.3 (0.4, 0.1)	<0.10 –1.7 (0.3, 0.1)	<0.11 –4.5 (0.8, 0.3)	<1.57 –170 (8.3, 1.9)	3.3 –250 (29.2, 16.9)[d]	<0.3 –6.2 (0.6, 0.2)
[46,48] Malawi, Lilongwe	Passive sampler (PUF)	December 2004 –December 2005 (n = 3)	Gaseous	–	NA	NA	NA	–	–	–	–	< dl – 4[e]	–
De Aar, South Africa				–	NA	NA	NA	–	–	–	–	< dl – 4[e]	–
Kalahari,South Africa				–	NA	NA	NA	–	–	–	–	< dl – 6[e]	
[53]; Marseille, France	High volume sampler (QFF)	March 2015 –January 2016 (n = 11)	Particulate	0.001 –0.007	0.07 –1.3	0.07 –1.3	0.02 –0.3	0.01 –0.4	0.01 –0.1	0.02 –0.5	1.1–15	2.2–18 (9.0)[b]	–
[61 [61] Across Europe	Passive sampler (PUF)	June-July 2002 (n = 71)	Gaseous	<0.5 –30	<8-80	<10-120	<2-20	<0.7 –15	< dl – 10	–	–	0.5 –250[f]	–
[59]; Canada	Passive sampler (PUF)	October 2007 –October 2008 (n = 19)	Gaseous	NA	NA	NA	NA	NA	NA	NA	NA	0.47 –110[g]	NA
[71]; Birmingham, UK	Passive sampler (PUF)	January 2012 –January 2013 (n = 8)	Gaseous	<0.23 –26	<0.30 –31	<0.49 –43	<0.45 30	<1.1 –70	<0.89 –57	<1.5 –57	<2.2 –1500	120 –1700[h]	[#] < 0.06 –408
[72]; China	High volume sampler (PUF + QFF)	October 2008 –July 2009 (n = 28)	Gaseous	NA	NA	NA	NA	NA	NA	NA	NA	7–470[i]	[#] 20 –1800
[74]; Great Lakes	High volume sampler (QFF)	January-December 2014 (n = 92)	Particulate	–	–	–	–	–	-	-	-	-	[##] 1.7 –5.2

QFF – Quartz fibre filter, PUF – Polyurethane foam, [#] Range, [##] Range of median concentrations, NA- Not Available, (-) – Not investigated, dl – detection limit.
[a] Σ_9 Range (mean, median).
[b] Σ_{27} Range (median).
[c] Σ_{14} Range.
[d] Σ_{19} Range (mean, median).
[e] Σ_3 Range.
[f] Σ_8 Range.
[g] Σ_{27} Range.
[h] Σ_{13} Range.
[i] Σ_9 Range.

3.8. Potential factors influencing the presence of PBDEs and HBCDD in African Air and Indoor Dust

BDEs - 28, 47, 99, 100 and 209 appear dominant in African air, with BDEs - 47, 99, 100, and 209 the most prevalent congeners in indoor dust. Combined, this suggests that the Penta-BDE and Deca-BDE formulations were the principal PBDE formulations present in products used in Africa. Intriguingly however, Castro-Jiménez et al. [53] reported BDE-183 was predominant in atmospheric particulate matter from Bizerte, Tunisia, suggesting appreciable Octa-BDE formulation usage. While light congeners (BDE-28, 47, 99, and 100) dominated air concentrations especially in the summer in Gauteng, South Africa [70] and are appreciably influenced by long range transportation, the frequent detection in air of BDE-209 signifies local or short-range inputs. In keeping with other locations globally, extensive use of electrical and electronic products, as well as flame-retarded soft furnishings are likely the principal sources of PBDEs and HBCDD in air and indoor dust in Africa. More specific to Africa, studies of locations near e-waste recycling and landfills indicate elevated concentrations, suggesting such waste-handling related activities constitute significant emission sources for these BFRs [64,70].

3.9. Polycyclic aromatic hydrocarbons (PAHs)

PAHs appear the most studied of the contaminants targeted in this review (Tables 5 and 6). Of particular note, is that several studies exist that report concentrations of PAHs in indoor air in Africa.

Table 4
Summary of concentrations of PBDEs and HBCDD in indoor settled dust from Africa and in other illustrative studies.

Study, Location, Sampling Period	Microenvironment (Sample number)	Concentration (ng/g) – Range (mean, median)									
		BDE-28	BDE-47	BDE-99	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209	Σ PBDEs	HBCDD
[65];Abraka and Warri, Nigeria, February –March 2019	Computer, photocopier, and printer workshops (n = 10)	<dl - 251 (153, 133)	<dl - 285 (208, 277)	<dl - 396 (121, 34)	<dl - 147 (58, 36)	<dl	<dl	<dl - 59.4 (59.4, 59.4)	<dl	35 - 1027 (457, 366)[a]	–
	Television, radio, stereo, and video player workshops (n = 20)	<dl - 392 (252, 262)	<dl - 581 (262, 200)	<dl –143 (64, 43)	<dl - 185 (66, 30)	<dl - 59.5 (56, 56)	<dl - 104 (54, 54)	<dl	<dl - 1770 (1238, 1301)	14.2–2578 (1112, 958)[a]	–
	Telephone and tablet workshops (n = 10)	113 - 332 (218, 257)	54 - 477 (244, 175)	<dl - 204 (100, 71)	<dl - 187 (86, 62)	<dl	<dl	<dl	<dl	179–872 (622, 704)[a]	–
[3]; Lagos, Nigeria, September–October 2014	Homes (n = 12)	<0.04–3.1 (1, 4)	2.2–50 (13, 8)	1.5–31 (17, 14)	<0.03–44 (8, 4)	<0.04–22 (5, 4)	<0.04 –3500 (450, 4)	2.9–90 (26, 18)	* 77–940 (420, 390)	–	–
	Offices (n = 18)	<0.04–65 (5, 1)	<2.8–100 (20, 14)	<0.04 –110 (28, 18)	<0.03–24 (7, 4)	<0.04–24 (5, 4)	<0.04–8 (2, <0.04)	4.3–350 (66, 26)	* < 0.11 –4900 (1200, 930)	–	–
	Cars (n = 16)	<0.04–65 (7, 1)	<0.05 –9300 (900, 28)	<0.04 –19000 (1700, 49)	<0.03 –3100 (330, 12)	<0.05 –6000 (720, 9)	<0.04 –6.4 (1, <0.04)	<0.04 –480 (83, 9)	*< 0.11 –52000 (10000, 780)	–	–
[7]; Lagos, Nigeria, September–October 2014	Homes(n = 10)	–	–	–	–	–	–	–	–	–	**(659, 394)
	Offices (n = 10)	–	–	–	–	–	–	–	–	–	** (376, 156)
	Cars (n = 10)	–	–	–	–	–	-	-	-	-	** (329, 297)
[80]; Cairo, Egypt, 2013	Homes (n = 17)	0.15–4 (0.7, 0.3)	0.34–375 (29, 1.7)	0.53 –509.8 (34.9, 2.7)	0.07–97.7 (7.2, 0.4)	0.54 –194.7 (27.8,6.3)	<0.04 –7.9 (4.9, 0.4)	0.27 –5.23 (1.7, 105)	2.20–591 (129, 40.2)	5.04–1918 (248, 57) [b]	** (20.7, 6.15)
	Cars (n = 9)	0.67–12.0 (2.5,1.2)	0.49–111 (25.9. 5.7)	1.51–123 (33.0,22.5)	0.09–25.1 (6.7,4.8)	4.03–74.9 (25.5,16.3)	<0.04 –3500 (5.9,3.6)	1.76 –43.5 (10.8, 5.8)	159–36927 (6813, 1540)	171–37440 (6943, 1608) [b]	** (47.7, 37.5)
	Workplaces (n = 5)	0.27–2.21 (1.0, 0.4)	0.75–23.5 (7.4, 2.3)	2.46–20.9 (11.2, 7.1)	0.16–2.03 (1.0, 0.6)	2.89–54.9 (30.0, 32.9)	<0.04 –6.4 (5.6, 0.8)	0.82 –6.85 (3.3, 2.3)	26.1 –72096 (14915, 3.7)	38.1 –72279 (14993, 425) [b]	** (27.6, 18.6)
[77]; Pretoria, South Africa, October 2010–April 2011	Homes (n = 31)	–	2.6	2.6	<0.13	<0.13	<0.13	-	[#] <1.8	<0.3–234 (18.3) [c]	–
[1]; South Africa, August–October 2012	Cars (n = 14)	<dl – 325 (49, 32)	37–1127 (269, 188)	63–2046 (502, 325)	<dl – 1218 (185, 134)	<dl – 2101 (375, 255)	<dl – 1017 (168, 76)	<dl – 2269 (392, 247)	128–5173 (1379, 845)	573 –11,833 (3319, 2771) [d]	–
[63]; Durban, South Africa, August-October/2012	Homes (n = 10)	1.12–30.0 (15, 12)	56.1–466 (183, 156)	150–1140 (541, 507)	<dl - 150 (47, 37)	33.6–182 (78, 65)	<dl – 134 (76, 97)	5.6–106 (44, 45)	59.2–2190 (731, 656)	689–3920 (1710, 1550) [d]	–
	Offices (n = 10)	<dl –54.9 (17, 14)	15.4–388 (135, 119)	45.5 –1930 (461, 148)	<dl – 95.1 (25, <dl)	<dl – 145 (84, 88)	<dl – 122 (53, 51)	37.2 –95.1 (70, 75)	78.4–2750 (678, 324)	266–5020 (1520, 871) [d]	–
	Computer laboratories (n = 11)	<dl –33.2 (11.5, 10.6)	<dl –51.9 (31.2, 31.8)	<dl – 138 (58.6,55.5)	<dl – 68.8 (21.6,20.4)	<dl – 1580 (310, 84.8)	<dl – 102 (40.1, 41.6)	73.9 –421 (175,145)	24.8–465 (170,145)	319–2720 (818, 628) [d]	–
[64]; Durban, South Africa, 2012–2013,	ICT workshops (n = 3)	67	136	121	< dl	1261	–	163	2862	4685 [d]*	–
	Recycling centres (n = 3)	<dl – 123	67–2968	77–6220	66–1042	270–1643	–	88–1677	1862 –27530	2632 –44203 [d]**	–
[78]; Makurdi, Nigeria, 2012	Homes (n = 10)	–	26–51 (47)	0.24–62 (46)	0.1–56 (43)	0.03–74 (50)	0.03–72 (35)	38.8–85 (30)	[##]79–202 (139)	45 [e]	–
	Offices (n = 11)	–	35.8–84.8 (46.0)	43.1–99.3 (54.2)	38.1–92.7 (51.1)	51.7–118 (67.1)	46.7 –110 (64.7)	1.0–124 (71.9)	[##]112–428 (140)	63 [e]	–
[79] Makurdi, Nigeria, April-June 2014	Cars (n = 12)	–	4.9–746 (99, 68)	0.01 –2562 (213, 14)	4–454 (65, 17)	378–585 (92, 16)	6.25 –378 (70, 19)	0.01 –110 (47, 25)	* 0.01–347 (137, 122)	159–736 [f]	–
[75]; Pretoria, South Africa, –	Offices (n = 16)	< dl	<dl – 81.9 (35.3, 44)	<dl – 127.7 (64.7, 76.5)	< dl	<dl – 12.5 (0.8, <dl)	< dl	< dl	<dl – 571 (52.6, <dl)	21.6–578.6 (169, 162) [g]	–
[7]; Annecy, France, August-October/2008	Homes (n = 9)	–	–	–	–	–	–	–	–	–	** (1209, 1351)
	Offices (n = 11)	–	–	–	–	–	–	–	–	–	** (4832,4740)

Table 4 (*continued*)

Study, Location, Sampling Period	Microenvironment (Sample number)	Concentration (ng/g) – Range (mean, median)									
		BDE-28	BDE-47	BDE-99	BDE-100	BDE-153	BDE-154	BDE-183	BDE-209	Σ PBDEs	HBCDD
	Cars (n = 7)	–	–	–	–	–	–	–	–	–	** (4721,5189)
[82]; Australia, June 2009–April 2011	Homes (n = 30)	0.7	36.9	56.8	9.1	6.4	5.1	4.6	*#415	60.4 –82400 (571) [h]	-
[41]; Ireland, August/2016–January/2017	Homes (n = 26)	NA	0.6–240 (26, 8)	<0.2–500 (45, 13)	NA	NA	NA	<0.3–33 (4, 1)	140 –650000 (58000, 13000)	NA	*1.3–43000 (2900, 490)
	Offices (n = 32)	NA	0.8–130 (16, 8)	<0.2–100 (26, 7)	NA	NA	NA	<0.3 –190 (11, 3)	500 –150000 (4200, 3500)	NA	*84–5200 (850, 380)
	Cars (n = 29)	NA	<0.1–130 (31, 24)	10.2–270 (70, 50)	NA	NA	NA	<0.3–92 (10, 4)	14–680000 (82000, 26000)	NA	*2400 –20000 (2800, 1300)
[83] Stockholm, Sweden, March-April & October-November/2006	Houses (n = 10)	<0.1–5.6 (1.3)	<0.5–230 (42)	<1–144 (52)	–	0.61–23 (6.6)	–	<0.7–49 (12)	*##53 –4000 (510)	–	15–990 (100)
	Offices (n = 10)	<0.1–5.4 (1.2)	14–390 (52)	14–770 (92)	–	4.3–100 (23)	–	15–160 (55)	500–13000 (1200)	–	190–5700 (300)
	Cars (n = 4)	<0.1–0.4 (0.2)	0.56–22 (7.4)	<1.5–30 (11)	–	0.25–6.7 (3.1)	–	<0.7–6.7 (2.2)	54–30000 (1400)	–	6.8–170 (54)

* Range (mean, median), ** (mean, median), # Median, # Range (mean), # Mean, *## Range (median), NA- Not Available, (-) – Not investigated, dl – detection limit.
[d]* Σ_8 (mean).
[d]**Σ_8 (Range).
[a] Σ_9 Range (mean, median).
[b] Σ_{14} Range (mean, median).
[c] Σ_{10} Range (median).
[d] Σ_8 Range (mean, median).
[e] Σ_7 median.
[f] Σ_7 Range.
[g] Σ_6 Range (mean, median).
[h] Σ_7 Range (median).

3.10. Concentrations of polycyclic aromatic hydrocarbons (PAHs) in outdoor air

The available information on concentrations of PAHs in African outdoor air are summarised in Table 5. Examination of Table 5 reveals concentrations in Africa are comparable on both intra- and inter regional scales. Unsurprisingly, elevated concentrations were mostly observed in studies that focused on the sum of both the gaseous and particulate phases or in those analysing the gaseous phase only, compared to those that measured concentrations only in the particulate phase. Elevated concentrations were however reported in airborne particulates collected in Greater Cairo ($\sum_{15}$PAHs 4787–5735 ng/m^3) and Giza (mean $\sum_{15}$PAHs 2310 ng/m^3), Egypt [47,85] and in the Niger Delta region of Nigeria ($\sum_{16}$PAHs 170–9200 ng/m^3) [11].

Concentrations of PAHs were reported to be higher in winter/cold/dry season than in the summer/warm/wet season [24,85,88–91], though Khairy and Lohmann [92] reported higher concentrations in the summer than winter with a suggestion of volatilisation/re-volatilisation of gaseous PAHs from polluted surfaces.

Concentrations of PAH in atmospheric particulates of 32 ng $\sum_{14}$PAHs/m^3, 9–45 ng $\sum_{14}$PAHs/m^3 and 8–15 ng $\sum_{12}$PAHs/m^3 reported for Alexandria (Egypt), Bizerte (Tunisia), and Cairo (Egypt) respectively [93,94]; Hassaniem et al., 2001), are consistent with the reports of Murillo et al. [95] (3–47 ng $\sum_{15}$PAHs/m^3) for Costa Rica. The reports of Fanoua et al. [33] (76–103 ng $\sum_{10}$PAHs/m^3) for Cotonou (Benin) and Kalisa et al. [24] (18–132 ng $\sum_{15}$PAHs/m^3) for Rwanda are comparable to those reported by Wu et al. [97] (1–180 ng $\sum_{18}$PAHs/m^3) for Mongolia (China) and Gaga et al. [98] (36–174 ng $\sum_{13}$PAHs/m^3) for Kocaeli (Turkey). However, higher concentrations were reported by Hasan and Khoder [85] (2310 (mean concentration) ng $\sum_{15}$PAHs/m^3) for Giza (Egypt) and [11] (170–9200 ng $\sum_{16}$PAHs/m^3) for the Niger Delta region of Nigeria.

Considering BaP (benzo[*a*]pyrene) as a marker for the complex atmospheric PAHs mixture, the concentrations of BaP recorded by Kalisa et al. [24] (2–11 ng/m^3) for Rwanda and Muendo et al. [99] (1–16 ng/m^3) for Kenya are comparable to the reports of Gaga et al. [98] for Turkey (5–18 ng/m^3). Moreover, the reports of Boudehane et al. [100] for Algeria (0.23–0.26 ng/m^3) and Arinaitwe et al. [101] (0.04–2.63 ng/m^3) for Uganda are comparable to Motelay–Massei et al. [102] (<0.001–0.18 ng/m^3) for Canada, and Menichini et al. [103] (0.1–4.6 ng/m^3) for Rome respectively.

3.11. Concentrations of PAHs in indoor air

Compared to outdoor air, fewer reports are available on concentrations of PAHs in indoor air in Africa. The concentrations reported in such studies are summarised in Table 6. Most reports on PAHs in indoor air in Africa are for the particulate phase only, with the exception of the studies of Boudehane et al. [100] for Ouargla, Algeria, Geldenhuys et al. [104] for South African platinum mines and Khedidji et al. [105] for student residence in Cubi (Algiers), Algeria. In general, concentrations in indoor air in Africa appear lower than those in outdoor air, except in cases where wood or charcoal were used as domestic energy sources [106,107] or where smoking occurs in the indoor environment [105]. While exact comparison is hindered by differences in the PAHs monitored in

Table 5
Summary of Concentrations of PAHs in Outdoor Air in Africa and selected other locations for comparison.

Study, Location, Sampling Period, Sample Number	Mode of sample collection (Collection medium, particulate size)	Benzo[*a*]pyrene range (ng/m^3)	∑ PAHs	Concentration range (ng/m^3)
Studies collecting particulate phase only				
[24]; Rwanda, April-May 2017 (wet season), n = not specified June 2017 (dry season), n = not specified	High volume air sampler (GFF, $PM_{2.5}$ and PM_{10})	*2.3–7.5 (PM_{10} not specified) *2.2–11 (PM_{10} not specified)	15	$PM_{2.5}$ = 15–51 PM_{10} = 18–103 $PM_{2.5}$ = 19–66 PM_{10} = 20–132
[115]; Algiers, Algeria, June-September/2016, (n = 92)	Active air sampler (PTFE, TSP)	0.12–0.42	22	5.6–7.5
[119]; Bizerte, Tunisia, March 2015–January2016, (n = 60)	High volume air sampler (QFF, TSP)	<dl – 0.85	34	0.5–17.8
[47]; Cairo, Egypt, December 2015–/February 2016, (n = not specified)	High volume air sampler (GFF, TSP)	**420–490	15	**4790–5740
[120]; Alexandria city, Egypt, January 2015 & February 2016, (n = 29)	High volume air sampler (QmF, TSP)	30–41	16	*323–502
[121]; Lagos and Ogun, Nigeria, October-November 2014, (n = 25)	Low volume air sampler (GFF, Particulates – size not specified)	NA	20	19.6–143
[118]; Assiut, Egypt, /September 2011, (n = 4)	Low volume pump (GFF, Particulates -Size not specified	*7.7–102	15	#579, 325
[90]; Cairo, Egypt, January February 2010), (n = 14) September-October 2010, (n = 14)	High volume air sampler (GFF, TSP)	1.2–7.7 1.5–7.9	15	##15–58 ##19–1800
[91]; Freetown, Sierra Leone, September 2010 & September 2011 (wet season), (n = 39) March 2011 (wet season), (n = 39)	Active air sampler (GFF, $PM_{2.5\ -10}$)	*0.07–4.8 *0.44–7.4	11	*3.3–40 *0.04–76
[86]; Northern Algeria, Algeria, July-August 2008 (n > 100)	Active air sampler (GFF, PM_{10})	*0.01–0.14	21	1.9–3.5
[85]; Giza (Dokki), Egypt, June-August 2007 (Summer), (n = 24) October 2007–February 2008 (Winter), (n = 24)	Calibrated vacuum pump (GFF, Particulate -Sizes not specified)	**71 **230	15	**550 **2310
[72]; Algiers, Algeria, September 2007, (n = not specified)	High volume air sampler (QFF, PM_{10})	NA	NA	**13
[75]; Algiers (Oued Smar), Algeria, August 2002–August 2003, (n = not specified)	Medium volume air sampler (QFF, PM_{10})	0.41–1.2	33	13–212
[87]; Northern Algeria, Algeria, July-October 2007, (n > 100)	Active air sampler (QFM, PM_{10})	0.5–50	28	12–24
[76]; Northern Algeria, Algeria, October 2006, (n = not specified)	High volume air sampler (QFF, PM_{10})	0.02–0.33	NA	0.5–3.0
[89]; Algiers, Algeria, July 2005–June 2006, Summer, (n = not specified) Winter, (n = not specified)	Medium-volume air sampler (QFF, PM_{10})	0.27–0.36 0.44–0.71	NA	11–19 16–29
[99]; Nairobi, Kenya, August-September 2003, (n = 24)	Mini pump (GFF, Particulates -Size not specified)	0.9–16	25	24–329
[33]; Cotonou, Benin, March 2001–August 2002, (n = not specified)	Battery operated pumps (GFF, Particulates -Size not specified)	NA	10	76–103
[93]; Alexandria, Egypt, July-August (year & sample number not specified)	High volume air sampler (GFF, Particulates – size not specified)	NA	14	32
[73]; Bouira province, Algeria, March-May 2014, (n = 43)	Low volume air sampler (QFF, PM_{10})	0.02–0.27	26	0.84–11
[107]; Allen Town, Sierra Leone, September 2011 (n = not specified)	Active air sampler (GFF, $PM_{2.5}$)	NA	11	*13–41
[105]; Algiers, Algeria, December 2009–March 2010, (n = not specified)	Low volume air sampler (QFF, PM_{10})	<dl – 0.5	26	8–87
[94]; Bizerte City, Tunisia, December 2009–February 2010, (n = 13)	Low volume air sampler (GFF, Particulates -Size not specified)	*< dl – 2	14	9.4–45 (25, 2.8)
[11]; Niger Delta, Nigeria, February-March (year not specified), (n = 14)	High volume air sampler (GFF, PM_{10})	NA	16	**170 - 9200
[108]; Algiers (Algeria City Area), Algeria, January-March 2000, (n = not specified)	Medium-volume aspirating pump (PTFE, PM_{10})	0.3–1	22	49–86
[119]; Algiers (Bab-Ezzouar), Algeria, August (year & sample number not specified)	Medium-volume aspirating pump (PTFE, PM_{10})	0.9–3.6	18	43–98
[52]; Cairo, Egypt, Summer (1997) (n = not specified) Winter (1997) (n = not specified)	High volume air sampler (GFF, PM_{10})	**0.10 **0.20	12	**7.5 **15
[95]; Costa Rica, January-November /2013, (n = not specified)	High volume air sampler (Collection medium not specified)	*0.19–0.20 *0.08–0.31	15	7.2–41 2.9–47

Table 5 (*continued*)

Study, Location, Sampling Period, Sample Number	Mode of sample collection (Collection medium, particulate size)	Benzo[*a*]pyrene range (ng/m^3)	∑ PAHs	Concentration range (ng/m^3)
	$PM_{2.5}$			
	PM_{10}			
[97];	Medium volume air sampler (QFF)	*1.67–8.21	18	0.58–145
Mongolia, China, November 2005, (n = not specified)	$PM_{2.5}$	*0.01–7.35		5.8–180
	PM_{10}			
[98];	Active air sampler (GFF, Particulates – Size not specified)	#*4.9 ± 2	13	#*36.3 ± 22.2
Kocaeli, Turkey,		#*18 ± 13.4		#*174 ± 131.5
January 2005–April 2006 (Summer), (n = 34)				
July 2005–October 2006 (Winter), (n = 34)				
Studies collecting vapour phase only				
[120];	High volume air sampler (PUF)	37.8–65.3	16	*400–720
Alexandria city, Egypt, January 2015 & February 2016, (n = 29)				
[100];	Passive air sampler (PUF)	0.23–0.26	18	143–147
Ouargla, Algeria, October-December 2014, (n = 15)				
[118];	Low volume air pump (PUF/XAD-2)	*0.8–6.2	15	#1012, 948
Assiut, Egypt, /September 2011, (n = 4)				
[88];	High volume air sampler (PUF)	#0.0009	42	390–990
Alexandria, Egypt,		#0.0008		240–1100
July 2010 (Summer), (n = 11)				
January 2011 (Summer), (n = 11)				
[85];	Calibrated vacuum pump (PUF/XAD-2)	**4.9	15	**1888
Giza (Dokki), Egypt,		**11.99		**3939
June–August 2007 (Summer), (n = 24)				
December 2007–February 2008 (Winter), (n = 24)				
[49];	Passive air sampler (PUF)	NA	16	###145–9680
Africa continent, January-June 2008, (n = 26)				
[123];	Semi-permeable membrane (SPMDs)	<dl – 55	9	4.9–135
Tangier, Morocco, October 2007, (n = not specified)				
[98];	Active air sampler (PUF)	*#0.2 ± 0.1	13	*#72 ± 26.9
Kocaeli, Turkey,		*#0.4 ± 0.3		*#250 ± 140
January 2005–April 2006 (Summer), (n = 34)				
July 2005–October 2006 (Winter), (n = 34)				
[102];	Passive air sampler (PUF)	<0.005–0.18	17	3.5–61
Greater Toronto, Canada, June 2000–July 2001, (n = 21)				
Studies collecting both vapour and particulate phase				
[101];	High volume air sampler (PUF + GFF)	0.04–2.63	30	19.3–311
Kakira, Uganda, (January 2000–August 2004),		0.09–0.99		13.3–126
(n = 39)		0.00–0.97		4.91–108
Entebbe 1, Uganda, (/March 2003–July 2004),				
(n = 22)				
Entebbe 2, Uganda, (October 2008–July 2010),				
(n = 56)				
[92];	High volume air sampler (PUF + QFF)	NA	44	330–1770
Alexandria, Egypt,		NA		170–1290
July-August 2010 (Summer), (n = not specified)				
December 2010–January 2011 (Winter), (n = not specified)				
[103];	High volume air sampler (PUF + QFF)	0.1–4.6	8	NA
Rome, sampling period and number not specified				

PTFE - Polytetrafluoroethylene membranes, TSP - Total Solid Particulates, GFF - Glass Fibre Filter, GmF - Glass Microfibre Filter, QFF - Quartz Fibre Filter, QFM - Quarts Filter Membrane, PUF – Polyurethane foam, PM - Particulate matter of aerodynamic sizes, NA - Not Available, dl – detection limit, *Range of means, ** Mean, # Mean, median, ## Range (pmol/m^3), ### $\sum_{16}$ Range (ng/sample), #*Mean ± sd.

different studies, the particulate concentrations reported by Yasaa et al. [108] (18–29 ng $\sum_{22}$PAHs/m^3) for Algeria and the reports for Sierra Leonean living rooms (9–20 ng $\sum_{11}$PAHs/m^3) [107] are comparable but lower than those reported by Fanoua et al. [33] (35–57 ng $\sum_{10}$PAHs/m^3) for Benin and by Geldenhuys et al. [104] for South African platinum mines (0.5–260 ng $\sum_{16}$PAHs/m^3). Elevated concentrations are however reported by Titcombe and Simcik [106] (<1–5040 ng $\sum_{32}$PAHs/m^3) for Tanzania and Taylor et al. [107] (97–1280 ng $\sum_{11}$PAHs/m^3) for Sierra Leonean kitchens.

Studies conducted in both India (4–952 ng $\sum_{18}$PAHs/m^3) [109] and Saudi Arabia (5–100 ng $\sum_{13}$PAHs/m^3) [110] exceed the concentrations reported by Yasaa et al. [108] for Algeria and Taylor et al. [107] for Sierra Leonean living rooms, and Fanoua et al. [33] for Benin, but lower than Titcombe and Simcik [106] for Tanzania and Taylor et al. [107] for Sierra Leonean kitchens. Concentrations reported by Geldenhuys et al. [104] for South African platinum mines (0.5–260 ng $\sum_{16}$PAHs/m^3) exceed those reported for Saudi Arabian homes (5–100 ng $\sum_{13}$PAHs/m^3) [110] but are lower than those reported for India (4–952 ng $\sum_{18}$PAHs/m^3) [109]. For gaseous-phase PAHs, the concentrations reported by Boudehane et al. [100] for Algeria (45–182 ng $\sum_{18}$PAHs/m^3) are exceeded by 381–1338 ng $\sum_{26}$PAHs/m^3 reported for Cubi (Algiers), Algeria, by Khedidji et al. [105]. However, intercontinental comparison indicates the concentrations reported for Algeria by Boudehane et al. [100] are within the range of the studies of Gouin et al. [111] for the USA (mean 55 ng $\sum_{20}$PAHs/m^3) and Oliveira et al. [112] for Portugal (range 24–149 ng $\sum_{18}$PAHs/m^3).

3.12. Concentrations of polycyclic aromatic hydrocarbons (PAHs) in indoor dust

Four out of the seven studies reporting concentrations of PAHs in indoor dust (Table 7) are from West Africa. Iwegbue et al. [113] reported concentrations of $\sum_{17}$PAHs 52–497 ng/g in kitchen dust collected from Nigeria. Further studies reported higher concentrations (256–2960 ng $\sum_{16}$PAHs/g) in workshop dust [114] and

Table 6
Concentrations of PAHs in Indoor Air in Africa and selected other locations for comparison.

Study, Location, Sampling Period, Sample Number	Mode of sample collection (Collection medium, particulate size)	Benzo[*a*]pyrene range (ng/m^3)	∑ PAHs	∑PAHs Concentration range (ng/m^3)
Studies collecting particulate phase only				
[106]; Njombe, Tanzania, February-March 2007, (n = 12)	PMASS (GFF, $PM_{2.5}$) Homes and secondary school	<dl – 767	32	<1–5040
[33]; Cotonou, Benin, March 2001–August 2002, (n = not specified)	Battery operated pumps (GFF, Particulates Size not specified) Homes	NA	10	35–57
[104]; South Africa, July–September 2012 (n = 12)	Battery operated personal sampler (QFF, Particulates size not specified) Platinum mines	2.1–128	16	0.47–260
[107] Allen Town, Sierra Leone, September 2011, (n = not specified)	Active air sampler (GFF, $PM_{2.5}$) Kitchen Living room	NA	11	97–1280* 8.9–20*
[108]; Algiers (Algeria City Area), Algeria, January-March 2000, (n = not specified)	Medium-volume aspirating pump (PTFE, PM_{10}) Fat manufacturing factory	0.1–0.4	22	18–29
[109]; Agra – Delhi, India, November 2006–June 2007, (n = not specified)	Hand (Active) air sampler (PTFE, Particulates sizes not specified) homes	2.76–22.35	18	4.1–950
[110]; Jeddah, Saudi Arabia, Sampling period not provided (n = 55)	Active air sampler (QFF, PM_{10}) Homes, hotels, and offices	< dl - 7.20	13	4.5–100
Studies collecting vapour phase only				
[100]; Ouargla, Algeria, 10–12/October-December 2014, (n = 15)	Passive air sampler (PUF) University (Offices and laboratories) Hospitals School	0.00–0.36 0.00–0.15 0.00–0.06	18	103–182 78–124 45–63
[104]; South Africa, July-September 2012, (n = 12)	Battery operated personal sampler (PDMS) Platinum mines	**140	16	10–18000
[105]; Algiers, Algeria, January-June 2010, (n = not specified)	Passive air sampling – Analyst II cartridge types	*<dl – 8.9	26	*381 - 1338
[111]; Fairbanks – Alaska, United States, December 2008 –March 2009, (n = 8)	Passive air sampler (PUF) Homes	< dl	20	**55
[112]; Oporto, Portugal, April-June 2013, (n = 204)	Active air sampler (PUF) Pre-schools	< dl	18	23.9–149

GFF - Glass Fibre Filter, QFF - Quartz Fibre Filter, PUF - Polyurethane foam, PDMS - Polydimethylsiloxane, PM - Particulate matter of aerodynamic sizes, PMASS - Personal Microenvironment Aerosol Speciation Samplers, PTFE - polytetrafluoroethylene membranes· NA – Not Available dl - detection limit, * Range of means, ** Average concentrations.

Table 7
Summary of Concentrations of PAHs in Indoor Settled Dust in Africa and selected other locations for comparison.

Study	Location	Sampling Period	Microenvironment	Benzo[*a*] pyrene	∑PAHs	∑PAHs Concentration range (ng/g)
[114]	Southern Nigeria, Nigeria	Year not specified (n = 40)	Electronic workshops	1–332	16	205–2963
[43]	Delta State, Nigeria	November–December 2016 (n = 60)	Homes)	nd - 1118	16	60–111914
[115]	Algiers, Algeria	June–December 2016 (n = 36)	Homes, schools, factory, and offices	0.45–1.8*	21	12–108*
[100]	Ouargia, Algeria	October 2014–January 2015 (n = 7)	University, hospital, school, and home	0.1–1.2**	18	17–89**
[42]	Cape Coast and Komenda Edina Eguafo Abrem, Ghana	November–December 2012 (n = 40)	Homes	–	15	50–6045
[77]	Western Kenya, Kenya	Not specified	Accumulated roof soot	–	15	16–710
[113]	Delta, Nigeria	2009 (n = 30)	Kitchen	< dl	17	37–497
[116]	Palermo, Italy	2006 (n = 16)	Homes	1.8–608	16	36–34453
[117]	Shanghai, China	Sampling period and number of samples not specified	University lecture theatres and dining halls	50–1320	18	9630–44130

* Range (ng/m^2/day).
** Range of means (ng/m^2).

(60–112,000 ng $\sum_{16}$PAHs/g) in home dust [43]. These concentrations reported by Iwegbue et al. [114] exceeded those observed in Ghana (50–6045 ng Σ_{15}PAHs/g) [42]. In Algeria, Boudehane et al. [100] reported $\sum_{18}$ PAHs mean concentrations (17–89 ng/m^2) in Ouargia, while Rabhi et al. [115] reported indoor dust deposition of $\sum_{18}$PAHs to fall in the range 12–108 ng/m^2/day in Algiers.

The reports of Iwegbue et al. [43] ($\sum_{16}$PAHs 60–111914 ng/g) for Nigeria home dust exceed the concentrations reported by Mannino et al. [116] ($\sum_{16}$PAHs 36–34453 ng/g) for Italy, and Peng et al. [117] for China ($\sum_{18}$PAHs 9630–44130 ng/g). Essumang et al. [42] however, reported lower concentrations for Ghana ($\sum_{15}$PAHs 50–6045 ng/g). Finally, the concentrations of BaP reported by Iwegbue et al. [43] for the Nigeria dust (nd – 1118 ng/g) are comparable with those reported in China by Peng et al. [117] (50–1320 ng/g) but are significantly higher than the report in Italy by Mannino et al. [116] (1.8–608 ng/g).

3.13. Potential factors influencing concentrations of PAHs in African outdoor and indoor air and indoor dust

Urbanisation and industrialisation appear important influences on PAHs in dust and air in Africa [43,49]. Based on interpretation of

PAH diagnostic ratios, traffic emissions appear particularly substantial sources [24,92,118–120]. Contamination arising from industrial emissions [99,121], open waste burning [90,91], petroleum production activities [11] and smoking in indoor environments [105] are also identified as important sources endemic to Africa. High densities of all such sources (with the exception of petroleum production) in urban centres are a likely explanation for the higher outdoor air concentrations in cities compared to rural communities. In contrast, wood and coal burning for domestic heating and cooking purposes is widespread in rural areas and may account for the elevated PAHs concentrations reported in some rural African indoor environments [106,113]. Consequently, exposure patterns in outdoor and indoor environments in Africa likely differ between rural and urban locations due to such differences in sources. Moreover, the tropical climate in many African countries has implications for on-going emissions to outdoor air as a result of enhanced volatilisation from contaminated surfaces [92,101].

4. Research priorities

This review highlights substantial evidence of the presence of PCBs, PBDEs, HBCDD, and PAHs in outdoor air and indoor dust from Africa at concentrations comparable to those reported in studies conducted in other continents. However, while data exists on concentrations of PAHs in African indoor air, there appears to be little or no information on PCBs, PBDEs, and HBCDD in indoor air from the African continent. We could not find any data on concentrations of our target contaminants in vehicle air in Africa. While several studies sampled the gaseous and particulate phases for PCBs, PBDEs, and HBCDD; most studies measuring PAHs in air focus on the particulate phase only. Given the frequently elevated temperatures in many African regions and the semi-volatile nature of the contaminants under discussion, it is recommended wherever possible that both gas and particle phases should be sampled to ensure that airborne concentrations are not underestimated. Moreover, reporting gas and particulate phase concentrations separately will facilitate better understanding of the impacts of tropical temperatures on gas-particle phase partitioning. We also highlight the following additional important information gaps and suggestions for future studies.

* Evaluation of the concentrations of PCBs and BFRs in air from a wide range of indoor environments (including vehicles) is required. Conducting such measurements simultaneously alongside measurements in outdoor air will permit better understanding of the extent to which each environment influences the other. This is important, as the hotter climate and stronger building ventilation in some African regions may mean that such relationships reported for temperate regions are not universally applicable in Africa.
* Monitoring of BFRs, PCBs, and PAHs in air and indoor dust at a range of rural and urban locations across Africa is recommended as this will help assess spatial trends and human exposure via inhalation and incidental dust ingestion.
* Finally, concentrations should be studied on a regular basis over extended periods at the same selected locations to facilitate elucidation of temporal trends of POPs in Africa and evaluation of the impacts of measures to reduce concentrations.

Declaration of competing interest

All co-authors have confirmed that there are no known conflicts of interest.

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