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Bruce-Vanderpuije, Pennante, Megson, David, Reiner, Eric, Bradley, Lee, Adu-Kumi, Sam and Gardella Jr., Joseph (2018) The state of POPs in Ghana- A review on persistent organic pollutants: Environmental and human exposure. *Environmental Pollution*, 245. pp. 331-342. ISSN 0269-7491

DOI: <https://doi.org/10.1016/j.envpol.2018.10.107>

Publisher: Elsevier

Version: Accepted Version

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Accepted Manuscript

The state of POPs in Ghana- A review on persistent organic pollutants: Environmental and human exposure

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PII: S0269-7491(18)32958-0

DOI: <https://doi.org/10.1016/j.envpol.2018.10.107>

Reference: ENPO 11798

To appear in: *Environmental Pollution*

Received Date: 30 June 2018

Revised Date: 22 October 2018

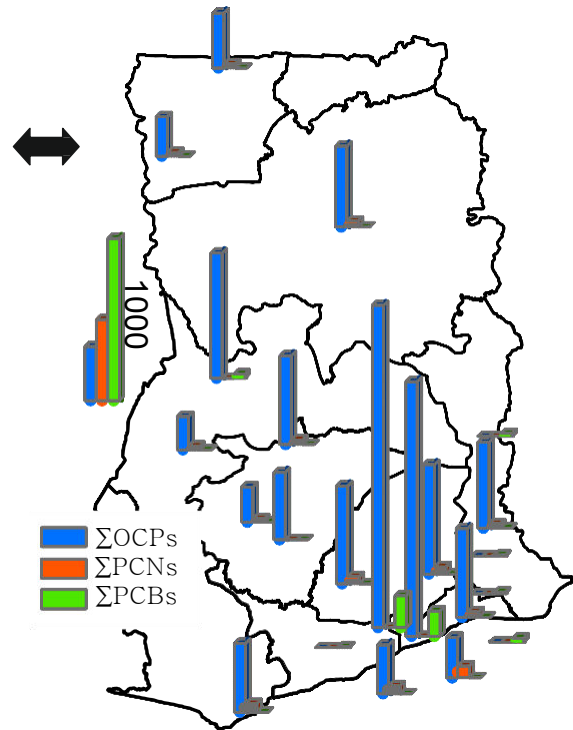
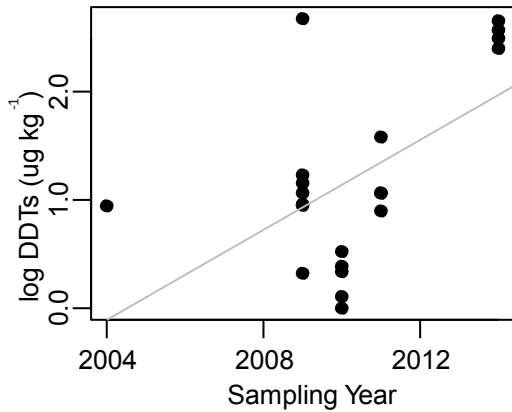
Accepted Date: 25 October 2018

Please cite this article as: Bruce-Vanderpuije, P., Megson, D., Reiner, E.J., Bradley, L., Adu-Kumi, S., Gardella Jr., J.A., The state of POPs in Ghana- A review on persistent organic pollutants: Environmental and human exposure, *Environmental Pollution* (2018), doi: <https://doi.org/10.1016/j.envpol.2018.10.107>.

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Pregnant Women
E-waste workers
Children
Farmers



1 **The State of POPs in Ghana- A Review on Persistent Organic Pollutants:**
2 **Environmental and Human Exposure.**

3
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18
19 **Abstract**

20 Ghana is one of the top pesticide users and highest persistent organic pollutant (POP) emitters
21 in sub-saharan Africa. Despite recent increases in published data, there is limited information
22 on how POP concentrations have changed, post ratification of the Stockholm Convention. As
23 a result, this review aims to address these knowledge gaps by collating available data that
24 reported POPs in Ghanaian environmental matrices, identify spatial and temporal trends, and
25 establish potential health risks. It is worth noting that Ghana has not developed its own

26 regulatory standards for POPs, but adapts United States Environmental Protection Agency
27 (USEPA) standards.

28 Results obtained showed concentrations in excess of USEPA regulatory standards for per-
29 and poly-fluoroalkyl sulphonates (PFASs) and dichlorodiphenyldichloroethane (DDD) in
30 water, polychlorinated and polybrominated dibenzo-p-dioxins and furans (PCDD/Fs and
31 PBDD/Fs) in e-waste soils, and polybrominated diphenyl ethers in aquatic organisms and
32 dairy products. The published studies do not cover major regions nationwide. The
33 inconsistency in methods and analytes measured, along with data scarcity in some regions,
34 makes it challenging to identify temporal trends. However, the data did indicate decreasing
35 concentrations of some legacy POPs in soil/sediment and aquatic organisms, with increasing
36 concentrations of some POPs in water, fish, fruits and vegetables. Studies that performed
37 health risks assessments were limited although the data indicated risks to e-waste workers,
38 some farmers and vulnerable sub-populations. This review identified potential human health
39 risks from POPs in the Ghanaian environment and the need for more consistent and
40 widespread monitoring program.

41
42 Capsule: This paper provides a critical review of studies of POPs in Ghana which can be used
43 as a reference for all of Africa, as well as other developing countries, for compliance with the
44 requirements for POPs monitoring in the e-waste, food and environmental sectors to inform
45 the mitigation of health risks.

46

47 Persistent Organic Pollutants; Environment; Human Health; Ghana; Africa

48

49

50

51 1. Introduction

52 Over several decades, the production of persistent organic pollutants (POPs) has resulted
53 in adverse toxicological effects to human and environmental health. Although POP emissions
54 have been restricted by the Stockholm Convention, exposure continues from a variety of
55 sources: industrial additives in polymers and pesticides, inappropriate waste disposal and
56 long-range transport (Birnbaum, 1994; Gioia et al., 2014; Herrman, 1993; Jones and De
57 Voogt, 1999; Stockholm Convention Secretariat, 2001; Vallack et al., 1998).

58
59 Despite adoption and entry into force of the Stockholm Convention in 2001 and 2003,
60 reports still confirm elevated POP concentrations. For instance, in North America, Europe
61 and Asia, POPs in aquatic organisms (Fisk et al., 2001; Hites et al., 2004; Jacobs et al., 2002;
62 Meng et al., 2007), sequestered in soil (Marvin et al., 2002; Zhang et al., 2002), air, dust,
63 particulate matter (Harner et al., 2004; Pozo et al., 2006; Strandberg et al., 2001), wildlife
64 (Mateo et al., 2016), bioaccumulation in serum (Patterson et al., 2009; Sjodin et al., 2008;
65 Thomas et al., 2006) and breastmilk (Kunisue et al., 2004; Schecter et al., 2003; Tanabe and
66 Kunisue, 2007) have been reported. Comparatively, in African countries, although pioneering
67 reports on POPs heavily focused on pesticides (Barakat et al., 2002; Clarke et al., 1997;
68 Darko et al., 2008b; Ntow, 2001; Schulz and Peall, 2001; van Wyk et al., 2001), few studies
69 in Ghana, South Africa and Egypt have documented dietary intake (Adu-Kumi et al., 2010;
70 Asante et al., 2011; Asante et al., 2013), concentrations in serum and breastmilk (Darnerud et
71 al., 2011; Hanssen et al., 2010; Wittsiepe et al., 2015), wildlife, notably birds of prey (Garcia-
72 Heras et al., 2018), atmospheric burdens (Hassan and Shoeib, 2015; Hogarh et al., 2012),
73 water (Essumang et al., 2017), soil, sediment and ash (Caravanos et al., 2011; Fujimori et al.,
74 2016; Nieuwoudt et al., 2009; Tue et al., 2016), and beach pellets (Ryan et al., 2012) for other
75 classes of POPs. Ghana was a signatory to the Stockholm Convention in 2001 and ratified it

76 in 2003 (EPA-Ghana, 2007). Obligations under the Convention for state parties largely
77 resulted in the ban of nine organochlorine pesticides (OCPs) in West Africa (Federal Ministry
78 of Environment Nigeria, 2009; L'Environnement et au Tourisme Guinea, 2012; MINISTERE
79 DE L'ENVIRONNEMENT ET DU CADRE DE VIE, 2007), in addition to PCBs and
80 polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs) (Stockholm Convention
81 Secretariat, 2001). This presents a challenge as Ghana is one of the top pesticide users and
82 POP emitters from major industrial complexes, the agricultural and health sectors (Osibanjo
83 et al., 2002). A map of Ghana is shown in Figure 1, identifying the ten regions. POPs in
84 Ghana are understudied; however, there are potential risks to environmental and human
85 health due to a legacy of widespread pesticide use, along with additional emerging industries
86 such as e-waste processing sites.

87
88 An initial baseline assessment of POPs in the first National Implementation Plan (NIP) in
89 2007 by Ghana's Environmental Protection Agency (EPA), showed limited information on
90 the production, importation, and usage (EPA-Ghana, 2007). A 2018 revised edition of the
91 NIP highlights inventories of 9,972 sources of PCBs. Approximately 1.4×10^8 kg of imported
92 electrical equipment and related wastes between 2009-2014 were estimated to contribute to
93 polybrominated diphenylethers (PBDEs). Previous exposure to OCPs were primarily as a
94 result of unsafe agricultural practices and pest eradication (EPA-Ghana, 2018). PCDD/Fs,
95 mixed halogenated compounds (PXDD/Fs), hexachlorobenzenes (HCBs) and PCB
96 contaminants were identified from a variety of sources including medical waste incineration,
97 vehicular transportation, and open-air burning of electronic waste (EPA-Ghana, 2018).

98
99 In recent years, importation of electronics to Ghana has promoted technological
100 growth, although less stringent regulations have contributed to legal and illegal electronic

101 wastes (Brigden et al., 2008). Conflicting views on environmental health risks (Asante et al.,
102 2012; Chan et al., 2007; Fu et al., 2008; Leung et al., 2008) and income generation from e-
103 waste scavenging (Oteng-Ababio, 2012; Oteng-Ababio et al., 2014a), necessitates
104 implementation of regulations to ban informal e-waste recycling and make provisions for
105 sound practices.

106

107 **1.1. Current Legal Framework for POPs management in Ghana**

108 In addition to the Stockholm Convention, the Basel and Rotterdam Conventions (ratified
109 in Ghana in 2003) integrate environmental justice principles, in recognition of hazards
110 pollutants may pose to humans and the environment (Basel Convention Secretariat, 2003;
111 Rotterdam Convention Secretariat, 2003). Contrary to Article 6 (1) d (i) and (ii) of the
112 Stockholm Convention, appropriate measures for handling and disposal of POPs e-wastes are
113 lacking in Ghana. Of relevance are the Environmental Protection Agency Act, 1994 (Act
114 490) (EPA-Ghana, 1994), and the Hazardous and Electronic Waste Control and Management
115 Act, 2016 (Act 917), for regulation of pesticides and wastes (EPA-Ghana, 2016). Act 917
116 identifies the need for appropriate recycling facilities for the proper disposal and management
117 of POPs e-waste and hazardous wastes.

118

119 **1.2. Methodology and Aims**

120 Recent and historic sources, and types of POPs, make the Ghanaian environment an
121 important study area; however, a systematic review of POPs is yet to be completed. This
122 study focuses on previously published data on the Stockholm Convention POPs. As there are
123 several individual Stockholm POPs, similar analytes and congeners were grouped and
124 compared to assess which classes of POPs need further focus. This study reviews POP data
125 for environmental matrices (Section 2), food (Section 3) and humans (Section 4). Data on

126 sample collection, preparation and analytical methods are presented in supplementary
127 information S2, and Table S1. POP concentrations in various environmental matrices were
128 compared with internationally accepted tolerance levels to estimate potential health risks. The
129 data gathered is considered in sections 5 and 6, and Table S6, presenting a critical evaluation
130 and identify considerations for future research prioritization.

131

132 Based on the criteria for a systematic review (Liberati et al., 2009), a literature search
133 of peer-review articles published from 2001 to present was conducted using Web of Science
134 and Scifinder databases. The following search terms were used: “persistent organic
135 pollutants”-POPs, “polychlorinated biphenyls”-PCBs, “polybrominated diphenylethers”-
136 PBDEs, “organochlorine pesticides”-OCPs, “polychlorinated dibenzo-p-dioxins and furans”-
137 PCDD/Fs, “polychlorinated naphthalenes”-PCNs, “perfluoroalkyl sulphonates”-PFASs and
138 “Ghana”. A total of 151 scientific papers were identified (88 from Web of Science, and an
139 additional 63 with Scifinder). Duplicate manuscripts were removed and the remaining papers
140 screened for suitability based on reporting of the following criteria: Stockholm POP
141 congeners, sampling location, type of sample, extraction and detection method, and
142 concentrations. This resulted in a total of 56 papers used to compile this review. Further, 8
143 papers on social impacts of POPs, the 2007 and 2018 revised NIP reports were reviewed. For
144 temporal trend analysis, the sum of DDTs: [o,p'-dichlorodiphenyltrichloroethane (DDT), p,p'-
145 DDT, o,p'- dichlorodiphenyldichloroethylene (DDE), p,p'-DDE, and o,p'-
146 dichlorodiphenyldichloroethane (DDD)], sum of HCHs (hexachlorocyclohexanes): [α -HCH,
147 β -HCH, γ -HCH, and δ -HCH], and sum of Endosulfans: endosulfan I, II and endosulfan
148 sulfates] were plotted against sampling year. The results of temporal and spatial trends are
149 summarized in supplementary information- S3 Temporal and Spatial Evaluations, and in the
150 conclusion section 5.

151 Several challenges need to be considered when comparing historical datasets. We
152 have attempted to address these in the supplementary information S1, but acknowledge the
153 resultant inevitable degree of uncertainty.

154

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155 2. POP Concentrations in the Ghanaian Environment

156 2.1. Air

157 POP concentrations in ambient air vary geographically and spatially, and depend on
158 inputs from emission sources. As with other environmental media, POPs partition to
159 particulate matter after pesticide spray application, from combustion processes, and
160 volatilization (Breivik et al., 2002; Jones, 1994). Table S2 and Figure S1 summarize POPs in
161 air in urban and rural areas in Ghana. Analytical methodologies are discussed in Table S1. A
162 review on baseline studies on Ghanaian regions on PCBs, OCPs, PCDD/Fs and PCNs is
163 described below.

164

165 2.1.1. PCBs

166 PCB concentrations in rural and urban areas ranged from below the limit of detection
167 (LOD) to 74 pg m^{-3} (Bogdal et al., 2013; Gioia et al., 2011; Pozo et al., 2009). The highest
168 total concentrations for 7 PCB congeners ranged between 38-74 pg m^{-3} for rural and urban
169 areas (Bogdal et al., 2013). Total concentrations at Wenchi-rural area (Eastern region) for 48
170 PCB congeners, for different sampling periods, were 35 pg m^{-3} and 68 pg m^{-3} (Pozo et al.,
171 2009). A similar contribution from other rural areas for 29 PCB congeners, was 33 pg m^{-3}
172 (Gioia et al., 2011). For urban areas- Greater Accra region, the lowest concentration range for
173 48 PCB congeners was in Kwabenya (range: 8.2-12.6 ng sample^{-1}); the highest measurement
174 was at East Legon (range: 6.9-20.3 ng sample^{-1}) (Klanova et al., 2009). Hazard risk
175 assessments for inhalation of ambient PCB air were not reported in studies reviewed, possibly
176 because of their minimal contribution (1-2%) to total exposure from direct inhalation as
177 opposed to dietary intake (WHO, 2000).

178

179 The maximum reported exposure concentrations for urban areas (74 pg m^{-3}) was
180 below the accepted World Health Organization (WHO) PCB concentration of 3 ng m^{-3} and
181 0.003 ng m^{-3} for urban and non-industrialized areas, respectively (WHO, 2000). Although
182 rural exposure concentrations exceeded 0.003 ng m^{-3} (WHO, 2000), associations of ambient
183 PCBs with health risks are low. USEPA suggests possible risk to result from continuous
184 inhalation of concentrations that exceed $1.0 \text{ } \mu\text{g m}^{-3}$ (USEPA, 1989). The current data reflects
185 background levels with evidence of minimal primary emissions from agricultural wastes,
186 vehicular transportation, electronic wastes dumping and indiscriminate burning of wastes.

187

188 2.1.2. OCPs

189 Total OCP concentrations in rural and urban areas ranged from below LOD to 5,296
190 pg m^{-3} (Adu-Kumi et al., 2012; Hogarh et al., 2014; Klanova et al., 2009; Pozo et al., 2009).
191 The mid to southern parts of Ghana were dominated by HCHs, DDTs, and endosulfans;
192 chlordanes and heptachlors were detected in the northern parts. The mean OCP
193 concentrations reported in rural-Wenchi (Eastern region), Lake Bosomtwe (Ashanti region),
194 suburban-Accra, and other sites ranged between $19.3\text{-}3,700 \text{ pg m}^{-3}$ (Adu-Kumi et al., 2012;
195 Hogarh et al., 2014; Klanova et al., 2009; Pozo et al., 2009).

196 The potential for health risks are low, as concentrations reported were below USEPA
197 estimated carcinogenic assessment inhalation risks, ranging from $9.7 \times 10^{-5}\text{-}0.0013 \text{ } \mu\text{g m}^{-3}$ for
198 selected OCPs (USEPA, 1989). Since their ban in 1985 (except for lindane- banned in 2001
199 and endosulfan- 2009 in Ghana), concentrations indicate recent pesticide usage in agricultural
200 sectors (EPA-Ghana, 2007). Spatial and temporal trends are displayed in Figures S1 and S2;
201 results are summarized in supplementary S3 and conclusion sections.

202

203 2.1.3. PCDD/Fs

204 One study in literature focused on PCDD/Fs in air. Concentrations of PCDD/Fs in
205 urban-Accra ranged between 370-2,200 pg sample⁻¹, with hazard risk assessment of 10-100
206 pg International (I)-Toxic Equivalency (TEQ) sample⁻¹ (0.2 pg I-TEQ m⁻³) (Klanova et al.,
207 2009). Industrial and statistical emission estimates from 2002 baseline inventory to 2015
208 indicate an increase from 665 to 1485 g TEQ PCDD/Fs in Ghana (EPA-Ghana, 2018).
209 Assuming a sampling volume between 300-600 m³ (Klanova et al., 2009), concentrations
210 exceed USEPA urban emission estimates of 0.1 pg m⁻³ (USEPA, 1989). At these
211 concentrations, a low to medium health risk of skin and eye irritation from PCDD/Fs
212 inhalation can occur (USEPA, 1989). The current data reflects background concentrations
213 with potential emissions from agricultural wastes, vehicular transportation, electronic wastes
214 dumping and burning of wastes (EPA-Ghana, 2018).

215

216 **2.1.4. PCNs**

217 One study has been completed on PCN emissions in Ghana. Total concentrations of 63
218 PCN congeners were low and high in the middle and southern belts: ~30 and 100 pg m⁻³.
219 TEQ calculations of 17 PCN congeners resulted in concentrations ranging between 0.5-6 fg
220 TEQ m⁻³ for dioxin-like (dl) toxicity (Hogarh et al., 2012). The potential for eye and skin
221 irritations, and liver tissue lesions to result from prolonged inhalation of ambient PCN
222 exposure are low, as emissions were lesser than WHO estimates (tri- to hexa-, and
223 octachloronaphthalene range: 0.1-5 mg m⁻³) for occupational exposure (WHO, 2001). PCNs
224 are yet to be banned in Ghana; the high emissions may be attributed to point sources
225 including industrial production sites: smelting and used car incineration. Additional sources
226 could be from volatilization and wind trajectories from illegal toxic waste dumped by
227 Trafigura in 2006 on the south coast of Cote d'Ivoire (White, 2008).

228

229 **2.2. Water**

230 POP exchange between the atmosphere, aquatic ecosystems and terrestrial surfaces
231 influence POP loadings in aquatic media and sediments (Jozef M. Pacyna, 2000). In Ghana,
232 lake, river and stream contamination can stem from agricultural run-off during rainy seasons,
233 and household use of pesticides. A review of data on OCPs, PFASs and PCBs in water is
234 described below. These studies highlight important findings which indicate potential
235 pesticide contamination in 3 of 5 drinking water sources in Ghana- River Densu, White Volta
236 (Volta Lake), and Pra River (Lake Bosomtwe).

237
238 Table S1 includes an analytical summary of POP residues in water, in Ghana. Temporal
239 trends in water are shown in Figure S3; results are summarized in supplementary S3 and
240 conclusion sections.

241 242 **2.2.1. PCBs**

243 Mean PCBs in Lake Bosomtwe ranged from 1,090-7,190 ng L⁻¹, with PCB-52 as the
244 dominant congener (Afful et al., 2013b). PCB concentrations exceeded USEPA maximum
245 allowable limit of 500 ng L⁻¹ in drinking water (USEPA, 2009). Majority of local
246 communities in Ashanti region depend on water and fish from Lake Bosomtwe; extensive
247 exposure to higher levels for extended time periods could potentially result in skin disorders
248 and immune deficiencies (USEPA, 2009).

249 250 **2.2.2. OCPs**

251 Residues of OCPs in water were greater in rural than urban areas. Mean OCPs in rural
252 water- streams around agricultural irrigation sites in Tono (Upper East Region) and
253 Akumadan (Ashanti Region), standing pipe water source, drinking groundwater from dug-

254 wells, the Volta Lake, and Lake Bosomtwe ranged from below the LOD-6,350 ng L⁻¹ (Afful
255 et al., 2013b; Akoto et al., 2016; Darko et al., 2008b; Fosu-Mensah et al., 2016; Kuranchie-
256 Mensah et al., 2012; Ntow, 2001; Ntow, 2005; Ntow et al., 2008a). Mean OCPs in urban
257 water-River Densu in Nsawam and Weija (Greater Accra Region), ranged from below the
258 LOD-180 ng L⁻¹ (Kuranchie-Mensah et al., 2012). OCP residues at Tono irrigation site were
259 below the LOD (Akoto et al., 2016). In both rural and urban waters, endosulfans were
260 present. Lake Bosomtwe was the most contaminated, with high concentrations of endosulfan
261 sulfate (5,630 ng L⁻¹) and p,p'-DDD (6,350 ng L⁻¹) (Afful et al., 2013b). In the above studies,
262 OCPs were below WHO MRLs for surface (WHO, 2017), and groundwater (WHO, 2006),
263 except for p,p'- DDD (6,350 ng L⁻¹ Lake Bosomtwe) (Afful et al., 2013b), which exceeded
264 the MRL of 1,000 ng L⁻¹ (WHO, 2017). The potential for carcinogenic risks to result from
265 oral exposure to OCPs below the MRLs are low; risk levels estimated by USEPA (for DDD,
266 DDT, DDE, aldrin, HCH) that can induce carcinogenic risks (for 1 in 10,000 persons) range
267 between 0.6-10 µg L⁻¹ (USEPA, 1989). Recent widespread use of endosulfan within the
268 agricultural sector, and potential illegal use of DDT, lindane, amongst other banned
269 pesticides in rural areas, are the suspected sources responsible for contaminating water
270 resources.

272 2.2.3. PFASs

273 Of the 15 perfluoroalkyl acids (PFAAs) congeners, high concentrations of
274 perfluorooctanoic acids (PFOAs) and perfluorooctane sulfonates (PFOSs) were detected in
275 two river basins- River Pra and Kakum, and tap water from rural areas. The mean PFOAs and
276 PFOSs concentrations ranged between 113-205 ng L⁻¹ for river basins, and 103-107 ng L⁻¹ for
277 tap water (Essumang et al., 2017). The sum of concentrations [PFOSs] + [PFOAs] at each
278 site, exceeded USEPA health advisory levels of 0.07 ng L⁻¹ in drinking water (USEPA,

279 2016). Potential health risks of thyroid disease, kidney and testicular cancer could result from
280 prolonged exposure to PFOSs-contaminated water (Essumang et al., 2017). The data reported
281 suggests that treatment of Pra and Kakum river basins for tap water is not efficient at
282 removing PFAA contaminants (Essumang et al., 2017). PFASs are yet to be banned in
283 Ghana; the limited data gathered as part of this review indicates there may be significant
284 PFAS contamination in Ghanaian drinking water.

285

286 **2.3. Soil and Sediment**

287 Pesticides introduced into soils are taken up by plants, degrade or transported to
288 groundwater and accumulate in sediments (Ilyina, 2007). POPs are hydrophobic in nature,
289 strongly bind to soil and sediments rich in organic carbon matter, and can be slow to
290 degradation processes (Van Metre and Mahler, 2005). Soil and sediment act as reservoirs or
291 sinks (Moeckel et al., 2008; Van Metre and Mahler, 2005); thus, long-term deposition make it
292 possible to detect accumulated POPs. A discussion on studies of PCBs, OCPs, PBDEs and
293 dioxin-like compounds (DLCs) in soil and sediment is given below. These studies indicate
294 contamination of soil and sediment was as a result of recycling, dismantling and combustion
295 of e-wastes, leakage of oils from transformer storage, and agricultural pesticide usage.
296 Residents and workers in close proximity to e-waste soils, and soils surrounding
297 transformers, can be exposed to pollutants from inhalation, dermal contact and ingestion of
298 deposits on food.

299

300 Table S1 includes an analytical summary of POPs in soil and sediment. Table S4 and S5
301 summarizes POP data in sediments. Temporal and spatial trends are shown in Figures S4 and
302 S5; results of trends are summarized in supplementary S3 and conclusion sections.

303

2.3.1. Soil and ash from e-waste sites

2.3.1.1. DLCs

Concentrations of dioxin-like PCBs (dlPCBs), PCDD/Fs and PBDD/Fs at Agbogbloshie e-waste site in Accra, were among the highest measured in Ghanaian soils. Soils from open-burning of electronic wastes and metal sites were contaminated with PBDFs: 83-3,800 $\mu\text{g kg}^{-1}$ dry weight (dw), followed by PCDFs: 11-390 $\mu\text{g kg}^{-1}$ dw, PCDDs: 6.6-120 $\mu\text{g kg}^{-1}$ dw, PBDDs: 0.12-4 $\mu\text{g kg}^{-1}$ dw and dlPCBs: 3.4-82 $\mu\text{g kg}^{-1}$ dw (Tue et al., 2016). Soils from open-burning sites were more contaminated than non-burning and non e-waste sites. The formation of dlPCBs was mainly attributed to catalytic abilities of Cu, Zn and Pb to release active chlorine and bromine species from e-waste combustion (Fujimori et al., 2016). Median WHO-TEQ for DLCs were 7.1 $\mu\text{g kg}^{-1}$ TEQ dw- open burning, 0.12 $\mu\text{g kg}^{-1}$ TEQ dw- non-burning and 0.00016 $\mu\text{g kg}^{-1}$ TEQ dw for non e-waste sites. Median TEQ values for e-waste soils exceeded the Canadian Soil Quality Guidelines (SQG) for PCDD/Fs (0.004 $\mu\text{g kg}^{-1}$ TEQ dw), indicating a potential risk to human health (Canadian Environmental Protection Act, 2002).

2.3.1.2. PBDEs

Concentrations of PBDEs in Agbogbloshie e-waste soils ranged between 16-100 $\mu\text{g kg}^{-1}$ dw. A variation in distribution of PBDE congeners was attributed to non-specific sources from e-waste activities. The dominant congener was PBDE 28, followed by PBDE 209 and PBDE 47 (Akortia et al., 2017). In contrast to the expected theory of lower brominated congeners partitioning to air particulates and higher brominated depositing on soil, lower brominated congeners was attributed to possibilities of atmospheric transport and deposition, and de-bromination of higher congeners during dismantling and open-air burning processes (Akortia et al., 2017; Oteng-Ababio et al., 2014b).

329

330 POPs in non-agricultural soils become a concern when there is a significant pathway
331 for exposure and receptors. The Agbogbloshie e-waste area is centred in a vegetable and food
332 market place surrounded by children of vendors, e-waste workers and the public. Despite the
333 large potential for exposure, no risk assessment of combined multiple exposure from
334 inhalation and food consumption has been completed. Given the elevated concentrations
335 recorded at this and other global e-waste sites, there may be a significant risk to human
336 health.

337

338 **2.3.2. PCBs in oil, and soil around transformer oil storage sites**

339 Using neutron activation analysis, higher total chlorine-³⁸Cl contents of PCBs were
340 measured by irradiation of 94 transformer oils collected from schools, hospitals, and water
341 treatment plants (71,340-266,920 $\mu\text{g kg}^{-1}$ wet weight (ww)) (Buah-Kwofie et al., 2011), in
342 comparison to soil extracts from 4 transformer oil storage sites (7,690-51,920 $\mu\text{g kg}^{-1}$ dw)
343 (John et al., 2014). The concentrations indicate major contamination of soils around
344 transformer storage sites, which present a local environmental and human health risk.

345

346 **2.3.3. Agricultural soil**

347 Studies of POPs in agricultural soils, in Ghana, were scarce and mainly focused on
348 OCPs in surface soil (Bentum et al., 2006; Fosu-Mensah et al., 2016; Ntow et al., 2007).
349 Variable depths of cored soils from cocoa farms and a tomato field in rural areas were
350 measured for OCPs. Mean concentrations of lindane in cocoa farm soils ranged between
351 LOD-50 $\mu\text{g kg}^{-1}$ dw in Brong Ahafo region (Fosu-Mensah et al., 2016), and between 2,100-
352 15,500 $\mu\text{g kg}^{-1}$ dw for Central region (Bentum et al., 2006). Lower mean concentrations of
353 p,p'-DDT, β -HCH and dieldrin residues in cocoa soils ranged between 5-50 $\mu\text{g kg}^{-1}$ dw

354 (Fosu-Mensah et al., 2016). Endosulfan dissipation in tomato soils showed α -endosulfan
355 (mean: 230-2300 $\mu\text{g kg}^{-1}$ dw) and endosulfan sulphate (mean: 40-650 $\mu\text{g kg}^{-1}$ dw) were
356 retained on top soil; β -endosulfan leached to lower depth (mean: 110-650 $\mu\text{g kg}^{-1}$ dw) (Ntow
357 et al., 2007). Concentrations of lindane exceeded the Canadian Environmental Quality
358 Guideline (CEQG) of 10 $\mu\text{g kg}^{-1}$ in agricultural soils (Canadian Council of Ministers of the
359 Environment, 1991); other OCPs monitored in soil were within the CEQG limits.

360

361 **2.3.4. Sediments**

362 POPs in sediments (from rivers, lakes, streams and coastal areas) are the most studied
363 matrix in Ghana. Although cored sediments reflect historical records of POP pollution,
364 surface sediments have been the focus, limiting the ability to understand sediment temporal
365 trends. A discussion on OCPs and PCBs in surface sediments from coastal marine, lakes,
366 streams, river basins and irrigation dams is given below.

367

368 **2.3.4.1. PCBs**

369 Mean PCB concentrations in sediment for 11 coastal areas (15.5-47.89 $\mu\text{g kg}^{-1}$ dw)
370 (Dodoo et al., 2012), was higher than for river sediments: 8 sites (0.57-32.2 $\mu\text{g kg}^{-1}$ dw)
371 (Hosoda et al., 2014), and lake sediments: 11 sites (1.09-19.17 $\mu\text{g kg}^{-1}$ dw) (Afful et al.,
372 2013b). The prevalence of higher concentrations of lower PCB congeners (PCB- 28 and 52)
373 (Afful et al., 2013b; Dodoo et al., 2012; Hosoda et al., 2014), supports the theory of sediment
374 historic contamination and subsequent degradation. To evaluate probable toxic effect levels
375 of PCBs on aquatic organisms, a comparison of sediment mean concentrations with the
376 CSQG, showed PCB concentrations fell within the accepted value of 21.5 $\mu\text{g kg}^{-1}$ dw (Afful
377 et al., 2013a, 2013b; Dodoo et al., 2012; Hosoda et al., 2014). A low health risk from human

378 exposure to coastal sediments was identified from hazard index (HI) assessment of < 1
379 (Hosoda et al., 2014).

380

381

2.3.4.2. OCPs

382 DDTs and HCHs were frequently detected in surface sediments covering coastal
383 Tema harbour areas, Weija dam and Nsawam (Densu river basin) in Greater Accra, Eastern
384 region, Lake Bosomtwe and 4 streams in Ashanti region, Volta lake (6 sites), and Tono
385 irrigation reservoir in the Northern region. The sum of DDTs were highest for irrigation
386 sediment (47-70 $\mu\text{g kg}^{-1}$ dw) (Akoto et al., 2016), followed by Volta Lake (61.30 $\mu\text{g kg}^{-1}$ dw)
387 (Ntow, 2005), coastal sediments (6.0-12.8 $\mu\text{g kg}^{-1}$ dw) (Botwe et al., 2017), lake sediments
388 (LOD-12.75 $\mu\text{g kg}^{-1}$ dw) (Afful et al., 2013b; Darko et al., 2008b), river basin sediments
389 (3.289 $\mu\text{g kg}^{-1}$ dw) (Kuranchie-Mensah et al., 2012), and streambed sediments (0.46 $\mu\text{g kg}^{-1}$
390 dw) (Ntow, 2001). Mean HCHs (0.75-13.6 $\mu\text{g kg}^{-1}$ dw) were much lower. Contributions of
391 aldrin and dieldrin were very low for sediment types (range: LOD- 0.95 $\mu\text{g kg}^{-1}$ dw), except
392 for irrigation sediment (aldrin: 90 $\mu\text{g kg}^{-1}$ dw) (Akoto et al., 2016). Similarly, low mean
393 concentrations of endosulfan sulphate were detected in all sediments (0.18-1.61 $\mu\text{g kg}^{-1}$ dw),
394 except for Lake Bosomtwe (37.68 $\mu\text{g kg}^{-1}$ dw) (Afful et al., 2013b).

395

396 Predictors of past or recent DDT usage are based on aerobic and anaerobic
397 degradation of DDT to DDE and DDD. Provided the ratio of DDT to its metabolites is <1,
398 past usage is predicted. Calculated ratios observed were <1 for river, lake and coastal
399 sediments (Afful et al., 2013b; Botwe et al., 2017; Darko et al., 2008b; Kuranchie-Mensah et
400 al., 2012; Ntow, 2005), indicating a decline in DDT usage with an increase of its metabolites
401 over the years.

402

403 Ecotoxicological risks of OCPs to aquatic organisms were evaluated by comparing
404 the sum of sediment mean concentrations to SQG. The additive effect of OCPs in river, lake,
405 coastal and irrigation sediments were below the lowest effect concentration (LEL) values of
406 the SQG (Table S3), an indication of low to medium ecotoxicological risk to aquatic
407 organisms. Lindane was identified as the major source of HCH contamination in sediments;
408 based on the predominance of γ -HCH which provides a ratio <1 for $\frac{\alpha\text{HCH}}{\gamma\text{HCH}}$ (Willett et al.,
409 1998)

410

411 2.3.5. Pellets

412 Plastic resin pellets are waste organic micropollutants released from plastic industries;
413 they pose a risk because they adsorb hydrophobic contaminants from aquatic media, and are
414 ingested in large quantities by aquatic organisms and sea birds. Two reports monitored beach
415 pellets as carriers of PCB contaminants in coastal rural and urban areas. The sum of mean
416 PCBs from 17 beaches ranged from 1-98.31 $\mu\text{g kg}^{-1}$ dw (Agbo and Abaye, 2016; Hosoda et
417 al., 2014). PCB concentrations in Accra: 39-69 $\mu\text{g kg}^{-1}$ dw (Ntow et al., 2011), and Tema-
418 Sakumono beaches: 29-46 $\mu\text{g kg}^{-1}$ dw (Ntow et al., 2011), 47.47 $\mu\text{g kg}^{-1}$ dw (Bempah et al.,
419 2012), were higher than rural areas: 1-15 $\mu\text{g kg}^{-1}$ dw (Ntow et al., 2011). Coastal pellets in
420 Accra and Tema were dominated by PCB-110, 138 and 180 (penta, hexa and hepta-PCBs),
421 with rural sites containing a lower proportion of higher chlorinated congeners. PCB
422 contamination of beach pellets was attributed to local inputs from e-waste dismantling and
423 dumping sites.

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3. POP concentrations in Food

POPs, once introduced into air, deposit on vegetation, soil and sediments, and bioaccumulate in aquatic fish and farm animals from ingestion of contaminated feed, sediment and plants. Marine and freshwater organisms are used as bioindicators because they accumulate POPs in higher concentrations than their aquatic environment (Gunther et al., 1999). For the majority of population that are not occupationally exposed to POPs, the main route of exposure (> 90% of POP intake) arises from dietary intake of animal products, fish, and seafood (Liem et al., 2000). Fruits and vegetables treated with pesticides, are another source of exposure (Liem et al., 2000).

Table S5 and Figure S6 summarize POP data in food. Methods of extraction, clean-up and analytical detection are summarized in Table S1. A discussion on POP concentrations, in edible fish, seafood, dairy products, beef, game meat, vegetables, fruits and cereals, is given below. Results from these studies indicate that intake of food of animal origin is the major contributor to OCPs and PCBs. On the other hand, relatively small PBDEs and hexabromocyclododecanes (HBCDs) contributions were obtained from fish (Asante et al., 2010; Asante et al., 2013), whilst vegetables, fruits and cereals contributed substantial amounts of OCPs. Data on Ghanaian dietary intake of PCDD/Fs and dIPCBs is scant.

3.1. Aquatic organisms

Freshwater fish is an important part of Ghanaian diet; it is a source of animal protein monitored for bioaccumulated POPs. Biomonitoring activities focused on fish types mostly consumed- tilapia and catfish. Muscle tissue is the commonly consumed fish part frequently analysed for contaminants. Investigations of POPs in molluscs in Ghana are limited, with three papers determining concentrations in oysters, mussels and cockles.

3.1.1. PCBs

Mean concentrations of PCBs in tilapia (*Tilapia zilli* and *Oreochromis niloticus*) and catfish (*Clarias gariepinus* and *Chrysichthys nigrodigitatus*) ranged from LOD-62 $\mu\text{g kg}^{-1}$ lipid weight (lw) (Asante et al., 2013; Kuranchie-Mensah et al., 2011). Mean PCB concentration, reported for tilapia from inland and coastal areas, was 62 $\mu\text{g kg}^{-1}$ lw (Asante et al., 2013); much lower mean concentrations in Lake Volta for tilapia and catfish ranged between 0.9-12.37 $\mu\text{g kg}^{-1}$ ww (Kuranchie-Mensah et al., 2011). Dominant congeners were PCBs- 153, 138 and 180 (Asante et al., 2013), although lower congeners PCBs- 28, 52, 101 and 99, contributed significant amounts (Asante et al., 2013; Kuranchie-Mensah et al., 2011). Potential risks of dietary exposure to tilapia and catfish from Lakes Volta and Weiija, and Benya and Keta lagoons were assessed to be low from hazard risk calculations (<1) (Asante et al., 2013; Kuranchie-Mensah et al., 2011), although authors proposed a more detailed assessment using HI and TEQ-WHO (Asante et al., 2013). Mean PCB concentrations were below the United States Food and Drug Administration action level (2000 $\mu\text{g kg}^{-1}$ ww) recommended for fish, suggesting a low health risk (USEPA, 2000).

PCB concentration in bivalves: cockles (*Anadara senilis*), oysters (*Crassostrea tulipa*) and mussels (*Perna perna*) along coastal rural areas (Lake Benya, Ningo, Sakumono) were

478 higher than for fish. Median concentrations for dry and wet seasons ranged between 1,200-
479 3,500 $\mu\text{g kg}^{-1}$ lw, and 1,500-2,100 $\mu\text{g kg}^{-1}$ lw (Otchere, 2005). Lower PCB concentrations in
480 mussels and oysters were detected in Narkwa, Ada and Anyanui; range: 3-11 $\mu\text{g kg}^{-1}$ ww
481 (Dodoo et al., 2013). Seasonal variation of PCBs in mussels was attributed to different source
482 inputs (terrestrial and marine) (Otchere, 2005). Dietary exposure to PCB-contaminated
483 bivalves are potentially high since median concentrations exceeded FDA action levels of
484 2000 $\mu\text{g kg}^{-1}$ lw for shellfish (USEPA, 2000). Results from calculated risks using PCB 118
485 (21-112.0 pg WHO-TEQ kg^{-1}) (Dodoo et al., 2013), exceeded the recommended Tolerable
486 Daily Intake of 2 pg WHO-TEQ kg^{-1} with potential risks of low birth weight and
487 neurobehavioural effects in children of exposed pregnant women. The calculated risk
488 contradicts the HI (<1), which indicated low risks of exposure to consumption of oysters and
489 mussels. Typically, TEQ is based on an additive result of 12 dlPCBs; however, the main
490 driver of TEQ is the most toxic: PCB 126. Therefore, an assessment including 12 dlPCBs,
491 rather than the use of PCB-118, would accurately assess risks. For both mussels and oysters,
492 tri and hepta-CBs were dominant congeners (Dodoo et al., 2013). The results indicate there
493 may be a significant risk from consumption of aquatic organisms. However, studies involving
494 determination of WHO-TEQ for PCBs and other DLCs, and a detailed quantitative risk
495 assessment is required to establish risk magnitude.

496

497 3.1.2. OCPs

498 DDTs were detected in fish obtained from lakes and reservoirs. The sum of mean
499 concentrations of DDTs in tilapia, were highest for Tono reservoir-Upper East Region
500 (*Sarotherodon galilaeus*: 250 $\mu\text{g kg}^{-1}$ ww) (Akoto et al., 2016); and Lakes Volta, Bosomtwe
501 and Weija for *Tilapia zilli* and catfish (*Clarias gariepinus*): 253.4 $\mu\text{g kg}^{-1}$ lw (Adu-Kumi et
502 al., 2010). Other studies detected lower mean concentrations of DDTs in tilapia in Lake

503 Bosomtwe- $8.88 \mu\text{g kg}^{-1}$ ww (Darko et al., 2008b), Lake Volta- $7.96 \mu\text{g kg}^{-1}$ ww (Kuranchie-
504 Mensah et al., 2011), $3.81 \mu\text{g kg}^{-1}$ ww (Gbeddy et al., 2012), and Weija Lake- $0.41 \mu\text{g kg}^{-1}$
505 ww.¹⁴⁴ The sum of mean DDTs concentration in catfish in Lake Bosomtwe, Volta and Weija
506 was $2206 \mu\text{g kg}^{-1}$ lw (Adu-Kumi et al., 2010); DDTs contamination in Tono reservoir was
507 $336 \mu\text{g kg}^{-1}$ ww in *Schilbe intermedius* (Akoto et al., 2016). HCHs bioaccumulation was high
508 in Kpando Torkor Lake (sum of mean concentration for *Tilapia zilli*: $41.6 \mu\text{g kg}^{-1}$ ww)
509 (Gbeddy et al., 2012). Mean HCHs and endosulfan concentrations in other fish species
510 ranged from LOD- $20.13 \mu\text{g kg}^{-1}$ ww (Darko et al., 2008b; Gbeddy et al., 2012; Kuranchie-
511 Mensah et al., 2011), and from LOD- $4.48 \mu\text{g kg}^{-1}$ ww respectively (Darko et al., 2008b;
512 Gbeddy et al., 2012; Kuranchie-Mensah et al., 2013). Other OCPs in fish included aldrin,
513 dieldrin, heptachlor and chlordane. Mean of chlordanes (trans-, cis-, oxy- chlordane) ranged
514 from LOD- $26.06 \mu\text{g kg}^{-1}$ ww (Adu-Kumi et al., 2010; Gbeddy et al., 2012; Kuranchie-
515 Mensah et al., 2011).

516

517 Mean OCP concentrations detected were below Food and Drugs Administration
518 (FDA) action levels for DDTs ($5000 \mu\text{g kg}^{-1}$ ww), chlordanes, aldrin, dieldrin, and heptachlor
519 ($300 \mu\text{g kg}^{-1}$ ww) for fish and shellfish from freshwater and marine sources (Food and Drug
520 Administration, 1995); an indication of low risk from OCP-contamination in Ghanaian fish.
521 Hazard risk calculation for consumption of OCP-contaminated fish varied in studies. Hazard
522 indices (HI) for fish consumption from Kpando Torkor lake indicated low risks (<1) for
523 HCH, DDT and γ -chlordane (Gbeddy et al., 2012); an HI of >1 was calculated for aldrin-
524 contaminated fish from Tono reservoir (Akoto et al., 2016). Other studies predicted potential
525 risks via consumption of OCP-contaminated fish, although HI were not calculated (Adu-
526 Kumi et al., 2010; Darko et al., 2008b; Kuranchie-Mensah et al., 2013).

527

528 3.1.3. PCDD/Fs and dlPCBs

529 The mean dlPCB concentration ($1200 \text{ pg g}^{-1} \text{ lw}$) in catfish and tilapia exceeded
530 PCDD/Fs ($23 \text{ pg g}^{-1} \text{ lw}$) in Lakes Bosomtwe, Volta and Weija (Adu-Kumi et al., 2010).
531 Estimated WHO-TEQs for dlPCBs and PCDD/Fs was $0.3 \text{ pg WHO-TEQ g}^{-1} \text{ lw}$ (Adu-Kumi
532 et al., 2010). Fish from the three lakes contained relatively low PCDD/Fs-dlPCBs, as
533 calculated WHO-TEQ value was below the permissible European Union (EU) Regulations
534 limit for fish: $8.0 \text{ pg WHO-TEQ g}^{-1} \text{ ww}$ (European Commission, 2006a), posing low health
535 risks.

536

537 3.1.4. PBDEs and HBCDs

538 Mean concentrations of PBDEs and HBCDs in tilapia from Lakes Weija and Volta,
539 and Benya and Keta lagoons were low. Mean PBDEs ranged from $0.89\text{-}19 \text{ }\mu\text{g kg}^{-1} \text{ lw}$;
540 HBCDs ranged from $0.04\text{-}2.2 \text{ }\mu\text{g kg}^{-1} \text{ lw}$. The least and most contaminated lagoons were
541 Keta and Benya. Dominant congeners- PBDE 47 and 209, were attributed to usage of penta
542 and deca-BDEs. Possibilities of degradation of PBDE-99 into PBDE-47, run-off from
543 contaminated areas into lakes, and de-bromination of hepta to hexa-BDEs contributed to their
544 accumulation (Asante et al., 2013). Possible contamination sources of lakes and lagoons were
545 credited to waste discharge from textile industries as well as improper wastewater treatment
546 (Asante et al., 2013). Mean PBDEs- $0.16 \text{ }\mu\text{g kg}^{-1} \text{ ww}$ for 15 PBDE-congeners, inclusive of 6
547 PBDEs (Asante et al., 2013), exceeded the maximum allowable concentrations for biota-
548 Directive 2013/39/EU: $0.0085 \text{ }\mu\text{g kg}^{-1} \text{ ww}$ for PBDE- 28, 47, 99, 100, 153 and 154
549 (European Commission, 2013). Low to medium risks of estrogenic activity from dietary
550 exposure to PBDE-contaminated fish are expected, although calculated HI were below the
551 critical value (<1). Low risks from dietary exposure to HBCDs in fish is predicted as the
552 mean HBCD concentration ($0.02 \text{ }\mu\text{g kg}^{-1} \text{ ww}$) (Asante et al., 2013) was below EU Directive-

553 2013/39/EU levels for biota ($167 \mu\text{g kg}^{-1} \text{ ww}$) (European Commission, 2013). Spatial and
554 temporal trends are displayed in Figures S6 and Figure 2; results of trends are summarized in
555 supplementary S3 and conclusion sections.

556

557 **3.2. Dairy products**

558 **3.2.1. OCPs**

559 Dietary exposure to six OCPs was assessed in dairy products. Mean DDTs
560 concentration in cheese ranged between LOD-298 $\mu\text{g kg}^{-1} \text{ lw}$. Lower mean concentrations
561 were detected in milk and yoghurt: 4.7-10 $\mu\text{g kg}^{-1} \text{ lw}$. The sum of mean OCP concentrations
562 were below WHO MRLs (Darko and Acquah, 2008a). Mean OCP concentrations in cheese
563 were below the extraneous WHO MRLs for lindane ($100 \mu\text{g kg}^{-1}$), aldrin ($150 \mu\text{g kg}^{-1}$),
564 dieldrin ($150 \mu\text{g kg}^{-1}$), endosulfan ($100 \mu\text{g kg}^{-1}$) and DDT ($500 \mu\text{g kg}^{-1}$), an indication of low
565 risk from dairy dietary exposure (Darko and Acquah, 2008a).

566

567 **3.2.2. PCBs**

568 A comparison of PCBs in raw cow milk in urban-Accra and rural-Asutuare (Eastern
569 region) showed the sum of mean PCBs ($27 \mu\text{g kg}^{-1} \text{ lw}$) in urban areas to be twice that for
570 rural ($14 \mu\text{g kg}^{-1} \text{ lw}$). A variation in PCB accumulation in cow milk were mainly attributed to
571 feeding habits (Asante et al., 2010). The mean concentrations for 15 PCB congeners were
572 below the maximum EU limits of $40 \mu\text{g kg}^{-1} \text{ lw}$ (European Commission, 2011). Low health
573 risk from milk consumption is expected; however, no studies were completed to ascertain the
574 TEQ.

575

576 **3.2.3. PBDEs**

577 In urban cow milk, concentrations ranged between 0.47-11 $\mu\text{g kg}^{-1}$ lw (mean: 2.3 μg
578 kg^{-1} lw). Lower concentrations were in rural milk (0.05-2.8 $\mu\text{g kg}^{-1}$ lw, mean: 1.0 $\mu\text{g kg}^{-1}$ lw).
579 Dominant congeners observed were PBDE-47 and 99. HBCD concentrations were below the
580 LOD (Asante et al., 2010). The mean concentrations of PBDE congeners exceeded allowable
581 concentrations set by EU Directive 2013/39/EU for biota (0.0085 $\mu\text{g kg}^{-1}$ ww for PBDE- 28,
582 47, 99, 100, 153 and 154) (European Commission, 2013). The results indicate potential risks
583 from dietary exposure to PBDEs in cow milk.

584

585 3.3. Meat

586 3.3.1. OCPs

587 Red meat (beef), is a significant source of protein for Ghanaian diet. Meat was
588 analysed to identify OCPs in beef fat, lean beef and grasscutter (bushmeat) obtained from
589 Kumasi-Ashanti region (Darko and Acquah, 2007), and Gomoa-Central region (Blankson-
590 Arthur et al., 2012). Elevated mean concentrations of DDE and DDT ranged between 32-545
591 $\mu\text{g kg}^{-1}$ lw for beef fat; much lower mean concentrations were in lean meat (range: 6-43 μg
592 kg^{-1} lw). Other OCPs ranged from 0.6-4.3 $\mu\text{g kg}^{-1}$ lw (lindane, dieldrin, endosulfan and
593 aldrin) for lean and beef fat. Mean concentrations of OCP analytes in grasscutter ranged from
594 0.15-0.78 $\mu\text{g kg}^{-1}$ lw. Mean concentrations of pesticides in lean and beef fat were below EPA
595 tolerance levels for DDT, DDE (5000 $\mu\text{g kg}^{-1}$ lw), endosulfan I, II and endosulfan sulfate
596 (beef muscle:13,000 $\mu\text{g kg}^{-1}$ lw, beef fat: 2000 $\mu\text{g kg}^{-1}$ lw), lindane and dieldrin (beef fat:
597 7000 and 200 $\mu\text{g kg}^{-1}$ lw respectively) (USDA, 2011). Concentrations detected were below
598 EPA tolerance levels, posing a low risk from dietary exposure to OCPs in food. Possible
599 sources were attributed to cattle feed-contamination with pesticides, and use of pesticides to
600 control ectoparasites (Darko and Acquah, 2007).

601

3.4. Cereal products, maize, cowpea and cocoa beans

3.4.1. OCPs

Infant and adult dietary exposures to OCPs were assessed in local and imported cereal-based food and cocoa beans. The highest mean OCP concentrations were recorded in cowpea and maize (LOD-123 $\mu\text{g kg}^{-1}$ dw) (Akoto et al., 2013), followed by cocoa beans (LOD-40 $\mu\text{g kg}^{-1}$ dw) (Okoffo et al., 2016), and cereal (LOD-22 $\mu\text{g kg}^{-1}$ dw) (Akoto et al., 2015b). The highest OCPs in cowpea and maize were β -HCH, β -endosulfan and DDTs (Akoto et al., 2013); that for cocoa beans: γ -HCH and p,p'-DDT (Okoffo et al., 2016). In cereal, the highest contributions were from γ -HCH (local cereal-22 $\mu\text{g kg}^{-1}$ dw) and β -HCH (imported cereal-14 $\mu\text{g kg}^{-1}$ dw) (Akoto et al., 2015b).

OCP concentrations in cereal, cowpea and maize exceeded MRLs, whereas concentrations in cocoa beans were below. Approximately 90% of baby food exceeded EU Directive-2006/125/EC of 10 $\mu\text{g kg}^{-1}$ assigned for pesticides in cereal (European Commission, 2006b). Similarly, OCPs in maize and cowpea exceeded EU MRL of 10 $\mu\text{g kg}^{-1}$ for β -HCH, and 50 $\mu\text{g kg}^{-1}$ for β -endosulfan, p,p'-DDE and DDD, an indication of medium risks from dietary exposure (European Commission, 2016). Calculated HIs were >1 (1.62-151), indicating carcinogenic and non-carcinogenic risk for infants and young children from pesticides in cereal (Akoto et al., 2015b). Health risks from consumption of cocoa beans were estimated as low, since pesticide concentrations were below EU MRLs (γ -HCH: 1000 $\mu\text{g kg}^{-1}$, β -HCH: 20 $\mu\text{g kg}^{-1}$, DDTs and dieldrin: 500 $\mu\text{g kg}^{-1}$, and aldrin: 50 $\mu\text{g kg}^{-1}$) (European Commission, 2016). Temporal trend plots could not be constructed due to the limited number of studies.

3.5. Fruits and vegetable crops

627 **3.5.1. OCPs**

628 Some fruits and vegetables obtained from market places in Accra, Kumasi, Tamale
629 and farm areas contained OCPs, which exceeded MRLs (Amoah et al., 2006; Bempah et al.,
630 2011a; Bempah et al., 2012; Bempah et al., 2011b; Bempah and Donkor, 2011; Ntow et al.,
631 2011; Owusu-Boateng and Amuzu, 2013). For a total of 1137 fruits and vegetables collected
632 from market, grocery, and farm sites, mean OCPs ranged between 2-200 $\mu\text{g kg}^{-1}$ ww
633 (Bempah et al., 2012; Bempah et al., 2011b; Bempah and Donkor, 2011). Mean
634 concentrations for vegetables- Accra, Kumasi and Tamale were 300-500 $\mu\text{g kg}^{-1}$ ww (Amoah
635 et al., 2006), whilst maximum concentration detected in Kumasi for fruits and vegetables was
636 190 $\mu\text{g kg}^{-1}$ ww (Bempah et al., 2011a). HI >1 calculated for OCPs showed endrin exceeded
637 the critical value for vegetables from Kumasi (Bempah et al., 2011a), posing a concern for
638 vegetable consumption. An assessment of low health risks of decreased thyroid function, and
639 weight loss from dietary exposure to OCPs in fruits and vegetables, can be expected.
640 Although most vegetables are edible in their raw states, washing and cooking before
641 consumption were advised to reduce ingestion of pesticide residues. Spatial and temporal
642 trends are displayed in Figures S6 and S7; results of trends are summarized in supplementary
643 S3 and conclusion sections.

644

645 **3.6. Honey**

646 **3.6.1. OCPs**

647 The concentrations of OCPs measured in honey from various areas in Western, Brong-
648 Ahafo and Ashanti Regions (LOD-0.01) were below recommended EU MRL (Darko et al.,
649 2017). Low health risks can be expected; however, risks from other POPs remain unknown as
650 studies are yet to be completed.

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662 **4. POP concentrations in Humans**

663 Biological monitoring of POPs, involving invasive and non-invasive techniques in
664 human, is performed using breastmilk, blood/serum, hair, saliva, semen, fingernails, and
665 urine. These give an indication of how POPs accumulate in the body via exposure, POPs
666 potentially transferred via placenta, and breastmilk from mother to child, and POPs (and their
667 metabolites) excreted through body fluids (Esteban and Castaño, 2009).

668

669 Figure S8 shows POPs data in breastmilk. Methods of extraction, clean-up and analytical
670 detection are summarized in Table S1. A discussion of POPs in human breastmilk and serum
671 is given below. Results from these studies indicate that the primary exposure route to POPs
672 bioaccumulation in human fluids is via food intake; a secondary exposure route include
673 inhalation from contaminated e-waste sites and farms. The presence of HCHs and DDTs

674 indicate their long-term usage and exposure to both breastfeeding mothers and infants within
675 the farming, fishing and e-waste communities in Ghana.

676

677 **4.1. Breastmilk**

678 **4.1.1. PCBs**

679 The risks of exposure to PCBs associated with intake of breastmilk by infants were
680 assessed in 304 breastmilk samples, by determining concentrations in exposed and unexposed
681 primiparae and multiparae mothers. Surprisingly, the sum of mean PCBs in non-
682 occupationally exposed mothers (for Accra, Kumasi and Tamale, 30-82 $\mu\text{g kg}^{-1}\text{ lw}$) (Asante
683 et al., 2011), were higher than for occupationally exposed mothers (4.4 $\mu\text{g kg}^{-1}\text{ lw}$) who lived
684 or worked at contaminated Agbogbloshie e-waste site in Accra (Asamoah et al., 2018). The
685 dominant congeners observed for non-occupationally exposed mothers were PCBs- 153, 138
686 and 180; occupationally exposed mothers was PCB 28. The unexpected concentrations could
687 indicate other exposure sources, in addition to cumulative years of occupational exposure.

688 Health risk assessments completed on occupationally exposed mothers indicated low
689 risks to infants: hazard quotient (HQ <1) (Asamoah et al., 2018). Low potential health risks
690 to breastfed infants is expected (Asante et al., 2011). However, concentrations were
691 consistently higher than the Agency for Toxic Substances and Disease Registry (ATSDR)
692 safety standard minimum risk level of 7 $\mu\text{g kg}^{-1}\text{ lw}$ (0.03 $\mu\text{g kg}^{-1}\text{ bw d}^{-1}$) for total PCBs in
693 human milk (Agency for Toxic Substances and Disease Registry, 2000).

694

695 **4.1.2. OCPs**

696 The mean concentrations of OCPs monitored in breastmilk ranged from LOD-490 μg
697 $\text{kg}^{-1}\text{ lw}$ (Ntow, 2001; Ntow et al., 2008b; Tutu et al., 2013). The mean concentrations
698 indicated the greatest exposure of mothers to DDTs and HCHs: 78 and 46 $\mu\text{g kg}^{-1}\text{ lw}$, and

699 below the LOD to $490 \mu\text{g kg}^{-1} \text{lw}$ in 2 farming communities (Ntow, 2001; Ntow et al.,
700 2008b); whilst Ada fishing community had the least exposure: 30 and $12 \mu\text{g kg}^{-1} \text{lw}$ (Tutu et
701 al., 2013). In an absence of OCP safety standards in humans, based on recommended safety
702 standards in rats, the equivalent milk OCP concentrations that would induce developmental
703 toxicity: $2300 \mu\text{g kg}^{-1} \text{lw}$ (van den Berg et al., 2017), were not exceeded.

704

705 **4.1.3. PBDEs and HBCDs**

706 The sum of mean concentrations of PBDEs and HBCDs ranged from 2.2-5.8 and 0.3-
707 $2.3 \mu\text{g kg}^{-1} \text{lw}$ respectively, in breastmilk from Accra, Kumasi and Tamale (Asante et al.,
708 2011). In comparison to Tamale ($2.5 \mu\text{g kg}^{-1} \text{lw}$), high mean concentrations in Accra ($4.8 \mu\text{g}$
709 $\text{kg}^{-1} \text{lw}$) and Kumasi ($5.8 \mu\text{g kg}^{-1} \text{lw}$) were attributed to greater exposure to PBDE-consumer
710 products and dietary preferences (Asante et al., 2011). PBDEs and HBCDs in breastmilk
711 provided a low exposure risk to breastfed infants, as the estimated daily intake were below
712 USEPA reference dose for PBDE-47 and 99 ($0.1 \mu\text{g kg}^{-1} \text{bw d}^{-1}$), and PBDE-153 ($0.2 \mu\text{g kg}^{-1}$
713 bw d^{-1}) in human milk (USEPA, 2008a, 2008b, 2008c).

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715 **4.2. Blood/serum**

716 Blood and serum from urban-Accra and rural areas-Offinso and Tono Irrigation sites in
717 occupationally exposed workers, were analysed for PCDD/Fs, PCBs, and OCPs (Ntow et al.,
718 2008b; Wittsiepe et al., 2015).

719

720 **4.2.1. PCDD/Fs and PCBs**

721 In a cross-sectional study of e-waste workers from Agbogbloshie with control group,
722 median PCDD/F concentrations in exposed populations ($6.2 \text{ pg WHO-TEQ g}^{-1} \text{lw}$, range:
723 $2.1\text{-}42.7 \text{ pg WHO-TEQ g}^{-1} \text{lw}$) were higher than in controls ($4.6 \text{ pg WHO-TEQ g}^{-1} \text{lw}$, range:

724 1.6-12 pg WHO-TEQ g⁻¹ lw) (Wittsiepe et al., 2015). Human exposure assessments to
725 PCDD/Fs and dlPCBs, from body burdens, are relevant when factors such as body weight,
726 fraction of PCDD/Fs and dlPCBs absorbed, and half-life are utilized in estimating daily
727 intakes. In an absence of health risk assessments of body burdens for both e-waste workers
728 and control groups, a feasible estimate of potential risks would have to be based on a
729 comparison of daily intake in order to compare with the recommended guideline range of 1-4
730 pg WHO-TEQ kg⁻¹ lw bw d⁻¹.

731 In contrast to PCDD/Fs, associations between PCBs in exposed and control
732 populations did not follow the expected trend. High concentrations were observed for PCBs-
733 138, 153 and 180 in control groups; geometric mean concentrations were significantly higher,
734 ~3 times that observed for exposed groups (PCB-138: 0.04 µg L⁻¹, PCB-153: 0.05 µg L⁻¹ and
735 PCB-180: 0.03 µg L⁻¹ whole blood). A strong correlation was observed between work
736 exposure time for e-waste workers who live on site; no correlation was found between PCBs
737 concentrations and age (Wittsiepe et al., 2015).

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739 4.2.2. OCPs

740 Serum of male and female vegetable farmers analysed for OCPs, indicated high mean
741 concentrations of dieldrin (127 µg kg⁻¹ lw) (Ntow et al., 2008b). No gender dependence of
742 total OCPs was observed on comparison of residues between male and female farmers. Mean
743 concentrations in male versus female serum were 10.6 vs 7.1 µg kg⁻¹ lw DDTs, 6.9 vs 8 µg
744 kg⁻¹ lw HCHs, and 134 vs 115 µg kg⁻¹ lw dieldrin, respectively (Ntow et al., 2008b).
745 Although HCHs are excreted during lactation, higher HCHs residue (8 µg kg⁻¹ lw) were
746 observed in female serum. Concentrations of OCPs detected in female serum could indicate
747 possible health risks to foetus when bioaccumulated contaminants are transferred
748 transplacentally (Ntow et al., 2008b). Although there are no tolerance levels for OCPs in

749 blood, an assigned reference dose of $0.5 \mu\text{g kg}^{-1} \text{bw d}^{-1}$ for DDT and $0.3 \mu\text{g kg}^{-1} \text{bw d}^{-1}$ for
750 HCH by USEPA, will not be exceeded if an average body weight of 60 kg is considered.

751

752 **4.3. Urine samples**

753 Urine is considered an ideal matrix for non-persistent chemicals; it has however been
754 used to monitor pesticides and their metabolites in several studies (Aprea et al., 2002). Within
755 farming communities in Ghana, improper and illegal use of pesticides can expose farmers to
756 absorption from the gut, by lungs and across skin. Long-term farming exposure activities
757 (above 30 d yr^{-1}) such as mixing and application of complex combinations of
758 insecticides/pesticides increased risks of chronic coughs, wheezing, and phlegm production.
759 Out of 8 OCPs determined in 100 urine samples, mean concentrations of β -HCH, heptachlor
760 and endosulfan sulphate (2800 ng L^{-1} , 3600 ng L^{-1} and 3300 ng L^{-1}) were noted to strongly
761 correlate with respiratory symptoms (Quansah et al., 2016).

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785 **5. Conclusions**

786 In this comprehensive and systematic review, our purpose was to collate and review
787 data from previous studies undertaken on Stockholm POPs in Ghana, since 2001. We
788 conducted a review on POPs in different matrices, compared concentrations against relevant
789 health criteria, and where data was available provided a discussion on spatial and temporal
790 trends (Figures S1-S8, supplementary information S3). Following this information, we
791 estimated the extent of POP contamination by identifying concern levels in matrices with
792 ranking from low, moderate, and high, to no data. POPs of high concern were assigned due
793 to data scarcity, increasing trends, and exceedances of relevant health criteria (Table S6). For
794 11 matrices and 10 POP-groups assessed in this review, 52% (58 instances) were classified as
795 no data, 8% (9 instances) were identified as high risk, 13.6% (15 instances) were identified as
796 moderate risk, and 25.4% (28 instances) were identified as low risk (Table S6).

797 In lakes and drinking water, high risks were observed for PCBs, DDTs and PFASs;
798 moderate risks were identified for several OCPs. Moderate risk for air was identified for

799 DDTs which showed an increasing trend (Figure S2). In water, moderate risks were
800 identified for endosulfans and HCHs, with increasing concentration trends (Figure S3). A
801 high risk was identified for PCDD/Fs in soil and sediment. Low and moderate risks were
802 identified for most OCPs in sediments, coupled with decreasing concentration trends for
803 HCHs and endosulfans (Figure S5).

804 Of the different food groups studied, a high risk was identified for PBDEs (in aquatic
805 organisms and dairy products), DDTs in fish (increasing trend) and Drins- sum of endrins and
806 dieldrins (in fruits and vegetables)- Figure S7. In maize, cowpea, fruits and vegetables,
807 moderate risks were identified for DDTs and HCHs. Low risks of DDTs and HCHs were
808 identified for meat, cocoa and dairy products. Large data gaps were identified for PBDEs,
809 HBCDs, PCDD/Fs and some emerging contaminants (PCNs and PFASs). Data on PCBs was
810 scarce.

811 High risks for humans were noted for both occupationally exposed individuals working
812 at e-waste sites and farming communities, and vulnerable subgroups through exposure to
813 POPs in food. The data reflects a high risk from PCBs due to concentrations in breastmilk
814 exceeding guideline values. A moderate risk was identified for DDTs. The data shows few
815 studies have been undertaken on a limited subset of POPs in humans.

816 The lack of a widespread consistent monitoring programme, and limited sampling
817 periods, make a robust assessment of spatial and temporal trends challenging. However, there
818 were statistically significant and non-significant temporal trends displaying a decrease in
819 concentrations of some legacy POPs (supplementary S3). The observed decline, although
820 non-significant for some legacy POPs, may be attributed to enforcement of the Stockholm
821 Convention, regulations and legal framework targeting POP elimination and reduction.
822 Conversely, significant and non-significant increases in DDTs, HCHs and endosulfans were

823 observed, and could potentially be attributed to illegal usage, and accumulation of banned
824 pesticides.

825

826 From the time-trend analyses, specific POP-pollutants (DDTs, HCHs and endosulfans)
827 in various media are discussed in supplementary information S3.7. These highlight multi-
828 media POP-pollutant occurrences, routes of fate and transport, and differing exposures within
829 the Ghanaian environment.

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834 **6. Knowledge gaps and recommendations**

835 Studies undertaken in Ghana over the past 17 years have reported POP concentrations
836 in a wide variety of matrices; however, these have been on local POP distributions. Another
837 issue is the lack of annual measurements and systematic monitoring over time for POPs in all
838 regions.

839

840 Temporal data have been assessed, but the majority of datasets do not show trends due
841 to limited sampling periods, and limited sample size. However, the data serves as a baseline
842 for future studies. We hope more consistent monitoring produces nationwide data, leading to
843 informed risk management strategies.

844

845 Continuous monitoring should involve screening of matrices via targeted and non-
846 targeted analyses for new and understudied POPs. This would reflect POP contaminants that

847 humans and wildlife are exposed to. This gap could be addressed with a complementary
848 non/semi-targeted analytical approach that would aid in identification of unknown
849 contaminants, and result in more robust risk assessments. Collection of data from a wider
850 range of analytes would be beneficial to help identify the main sources of POPs and establish
851 their importance in different regions. Non-targeted analyses of archived sample extracts could
852 be investigated to assess spatial and temporal trends in data deficient areas.

853 Table S6 shows a general lack of human, animal and wildlife exposure data. There is no
854 data for various matrices including indoor and outdoor air exposure assessment in
855 workplaces/homes, cored sediments, ground and bore-hole water, wildlife-avian population
856 data, amongst others. To address these gaps in knowledge, further studies would be required.
857 Of high importance would be human exposure studies which could include collection of
858 serum and breastmilk samples from vulnerable groups, occupationally exposed workers, and
859 the general population. Analyses of these samples should ideally be coupled with dietary
860 patterns, and workplace/home exposure hazards in questionnaires to clearly correlate POP
861 concentrations with socio-demographic characteristics.

862 A potential decline in legacy POPs in Ghana can be foreseen with low-toxicity pesticide
863 alternatives and regulations implemented by EPA-Ghana. However, more consideration
864 could be placed on emerging contaminants (such as PFASs and HFRs), and unintentionally
865 produced POPs (PCDD/Fs, PBDD/Fs, PCNs and dlPCBs), as trends of these contaminants in
866 the environment are less well understood. Similar trends and data gaps identified in this
867 review may be expected in other developing African countries, which highlight these trends
868 as an important area for future study.

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References

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3 Adu-Kumi, S., Kareš, R., Literák, J., Borůvková, J., Yeboah, P.O., Carboo, D., Akoto, O.,
4 Darko, G., Osae, S., Klánová, J., 2012. Levels and seasonal variations of
5 organochlorine pesticides in urban and rural background air of southern Ghana.
6 *Environ Sci Pollut Res* 19, 1963-1970.
- 7 Adu-Kumi, S., Kawano, M., Shiki, Y., Yeboah, P., Carboo, D., Pwamang, J., Morita, M.,
8 Suzuki, N., 2010. Organochlorine pesticides (OCPs), dioxin-like polychlorinated
9 biphenyls (dl-PCBs), polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo
10 furans (PCDD/Fs) in edible fish from Lake Volta, Lake Bosomtwi and Weija Lake in
11 Ghana. *Chemosphere* 81, 675-684.
- 12 Afful, S., Awudza, J.A., Osae, S., Twumasi, S.K., 2013a. Determination of indicator
13 polychlorinated biphenyls (PCBs) by gas chromatography-electron capture detector.
14 *Chemosphere* 93, 1556-1560.
- 15 Afful, S., Awudza, J.A., Osae, S., Twumasi, S.K., 2013b. Persistent organochlorine
16 compounds in the water and sediment samples from the Lake Bosomtwe in Ghana.
17 *Am Chem Sci J* 3, 434-448.
- 18 Agbo, I.A., Abaye, D., 2016. Levels of polychlorinated biphenyls in plastic resin pellets from
19 six beaches on the Accra-Tema coastline, Ghana. *J Health Pollut* 6, 9-17.
- 20 Agency for Toxic Substances and Disease Registry, 2000. Toxicological profile for PCBs. In:
21 U.S. Department of Health and Human Services PHS (ed). Agency for Toxic
22 Substances and Disease Registry, Atlanta, GA, USA.
- 23 Akortia, E., Olukunle, O.I., Daso, A.P., Okonkwo, J.O., 2017. Soil concentrations of
24 polybrominated diphenyl ethers and trace metals from an electronic waste dump site
25 in the Greater Accra Region, Ghana: implications for human exposure. *Ecotox*
26 *Environ Safe* 137, 247-255.
- 27 Akoto, O., Andoh, H., Darko, G., Eshun, K., Osei-Fosu, P., 2013. Health risk assessment of
28 pesticides residue in maize and cowpea from Ejura, Ghana. *Chemosphere* 92, 67-73.
- 29 Akoto, O., Azuure, A.A., Adotey, K.D., 2016. Pesticide residues in water, sediment and fish
30 from Tono Reservoir and their health risk implications. *SpringerPlus* 5, 1849.
- 31 Akoto, O., Oppong-Otoo, J., Osei-Fosu, P., 2015b. Carcinogenic and non-carcinogenic risk
32 of organochlorine pesticide residues in processed cereal-based complementary foods
33 for infants and young children in Ghana. *Chemosphere* 132, 193-199.
- 34 Amoah, P., Drechsel, P., Abaidoo, R., Ntow, W., 2006. Pesticide and pathogen contamination
35 of vegetables in Ghana's urban markets. *Arch Environ Con Tox* 50, 1-6.
- 36 Aprea, C., Colosio, C., Mammone, T., Minoia, C., Maroni, M., 2002. Biological monitoring
37 of pesticide exposure: a review of analytical methods. *J Chromatogr B* 769, 191-219.
- 38 Asamoah, A., Essumang, D.K., Muff, J., Kucheryavskiy, S.V., Søggaard, E.G., 2018.
39 Assessment of PCBs and exposure risk to infants in breast milk of primiparae and
40 multiparae mothers in an electronic waste hot spot and non-hot spot areas in Ghana.
41 *Sci Total Environ* 612, 1473-1479.
- 42 Asante, K.A., Adu-Kumi, S., Nakahiro, K., Takahashi, S., Isobe, T., Sudaryanto, A.,
43 Devanathan, G., Clarke, E., Ansa-Asare, O.D., Dapaah-Siakwan, S., Tanabe, S., 2011.
44 Human exposure to PCBs, PBDEs and HBCDs in Ghana: temporal variation, sources
45 of exposure and estimation of daily intakes by infants. *Environ Int* 37, 921-928.
- 46 Asante, K.A., Agusa, T., Biney, C.A., Agyekum, W.A., Bello, M., Otsuka, M., Itai, T.,
47 Takahashi, S., Tanabe, S., 2012. Multi-trace element levels and arsenic speciation in
48 urine of e-waste recycling workers from Agbogbloshie, Accra in Ghana. *Sci Total*
49 *Environ* 424, 63-73.

- 50 Asante, K.A., Sudaryanto, A., Devanathan, G., Bello, M., Takahashi, S., Isobe, T., Tanabe,
51 S., 2010. Polybrominated diphenyl ethers and polychlorinated biphenyls in cow milk
52 samples from Ghana. *Interdisciplinary Studies Environ Chem*, 191-198.
- 53 Asante, K.A., Takahashi, S., Itai, T., Isobe, T., Devanathan, G., Muto, M., Agyakwah, S.K.,
54 Adu-Kumi, S., Subramanian, A., Tanabe, S., 2013. Occurrence of halogenated
55 contaminants in inland and coastal fish from Ghana: levels, dietary exposure
56 assessment and human health implications. *Ecotox Environ Safe* 94, 123-130.
- 57 Barakat, A.O., Kim, M., Qian, Y., Wade, T.L., 2002. Organochlorine pesticides and PCB
58 residues in sediments of Alexandria Harbour, Egypt. *Mar Pollut Bull* 44, 1426-1434.
- 59 Basel Convention Secretariat, 2003. *Basel Convention on the Control of Transboundary
60 Movements of Hazardous Wastes and their Disposal*, UNEP.
- 61 Bempah, C.K., Buah-Kwofie, A., Denutsui, D., Asomaning, J., Tutu, A.O., 2011a.
62 Monitoring of pesticide residues in fruits and vegetables and related health risk
63 assessment in Kumasi Metropolis, Ghana. *Res J Env Earth Sci* 3, 761-771.
- 64 Bempah, C.K., Buah-Kwofie, A., Enimil, E., Blewu, B., Agyei-Martey, G., 2012. Residues of
65 organochlorine pesticides in vegetables marketed in Greater Accra region of Ghana.
66 *Food Control* 25, 537-542.
- 67 Bempah, C.K., Donkor, A., Yeboah, P.O., Dubey, B., Osei-Fosu, P., 2011b. A preliminary
68 assessment of consumer's exposure to organochlorine pesticides in fruits and
69 vegetables and the potential health risk in Accra Metropolis, Ghana. *Food Chem* 128,
70 1058-1065.
- 71 Bempah, C.K., Donkor, A.K., 2011. Pesticide residues in fruits at the market level in Accra
72 metropolis, Ghana, a preliminary study. *Environ Monit Assess* 175, 551-561.
- 73 Bentum, J., Essumang, D., Dodoo, D., 2006. Lindane and propoxur residues in the top soils
74 of some cocoa growing areas in five districts of the Central region of Ghana. *Bull
75 Chem Soc Ethiop* 20, 193-199.
- 76 Birnbaum, L.S., 1994. Endocrine effects of prenatal exposure to PCBs, dioxins, and other
77 xenobiotics: implications for policy and future research. *Environ Health Persp* 102,
78 676-679.
- 79 Blankson-Arthur, S., Tutu, A., Fosu, P., Mensah, H., Denutsul, D., Palm, L., Atiemo, S.,
80 Kwofie, A., 2012. Concentration of organochlorine pesticide residue in game meat
81 from the Gomoa East district of Ghana. *Elixir Pollution* 49, 9739-9742.
- 82 Bogdal, C., Scheringer, M., Abad, E., Abalos, M., Van Bavel, B., Hagberg, J., Fiedler, H.,
83 2013. Worldwide distribution of persistent organic pollutants in air, including results
84 of air monitoring by passive air sampling in five continents. *TrAC Trends Anal
85 Chem* 46, 150-161.
- 86 Botwe, B.O., Kelderman, P., Nyarko, E., Lens, P.N.L., 2017. Assessment of DDT, HCH and
87 PAH contamination and associated ecotoxicological risks in surface sediments of
88 coastal Tema Harbour (Ghana). *Mar Pollut Bull* 115, 480-488.
- 89 Breivik, K., Sweetman, A., Pacyna, J.M., Jones, K.C., 2002. Towards a global historical
90 emission inventory for selected PCB Congeners-a mass balance approach: 2.
91 Emissions. *Sci Total Environ* 290, 199-224.
- 92 Brigden, K., Labunska, I., Santillo, D., Johnston, P., 2008. *Chemical Contamination at E-
93 waste Recycling and Disposal Sites in Accra and Korforidua, Ghana*. Amsterdam:
94 Greenpeace.
- 95 Buah-Kwofie, A., Yeboah, P.O., Pwamang, J., 2011. Determination of levels of
96 polychlorinated biphenyl in transformers oil from some selected transformers in parts
97 of the Greater Accra region of Ghana. *Chemosphere* 82, 103-106.

- 98 Canadian Council of Ministers of the Environment, 1991. Canadian Environmental Quality
99 Guidelines on Hexachlorocyclohexane: Soil Quality for the Protection of
100 Environmental and Human Health.
- 101 Canadian Environmental Protection Act, 2002. Canadian Soil Quality Guidelines for the
102 Protection of Environmental and Human Health.
- 103 Caravanos, J., Clark, E., Fuller, R., Lambertson, C., 2011. Assessing worker and
104 environmental chemical exposure risks at an e-waste recycling and disposal site in
105 Accra, Ghana. *J Health Pollut* 1, 16-25.
- 106 Chan, J.K., Xing, G.H., Xu, Y., Liang, Y., Chen, L.X., Wu, S.C., Wong, C.K., Leung, C.K.,
107 Wong, M.H., 2007. Body loadings and health risk assessment of polychlorinated
108 dibenzo-p-dioxins and dibenzofurans at an intensive electronic waste recycling site in
109 China. *Environ Sci Technol* 41, 7668-7674.
- 110 Clarke, E., Levy, L., Spurgeon, A., Calvert, I., 1997. The problems associated with pesticide
111 use by irrigation workers in Ghana. *Occup Med* 47, 301-308.
- 112 Darko, G., Acquah, S., 2007. Levels of organochlorine pesticides residues in meat. *Int J*
113 *Environ Sci Technol* 4, 521-524.
- 114 Darko, G., Acquah, S.O., 2008a. Levels of organochlorine pesticides residues in dairy
115 products in Kumasi, Ghana. *Chemosphere* 71, 294-298.
- 116 Darko, G., Addai Tabi, J., Adjaloo, M.K., Borquaye, L.S., 2017. Pesticide residues in honey
117 from the major honey producing forest belts in Ghana. *J Environ Public Health* 2017.
- 118 Darko, G., Akoto, O., Oppong, C., 2008b. Persistent organochlorine pesticide residues in
119 fish, sediments and water from Lake Bosomtwi, Ghana. *Chemosphere* 72, 21-24.
- 120 Darnerud, P.O., Aune, M., Larsson, L., Lignell, S., Mutshatshi, T., Okonkwo, J., Botha, B.,
121 Agyei, N., 2011. Levels of brominated flame retardants and other persistent organic
122 pollutants in breast milk samples from Limpopo province, South Africa. *Sci Total*
123 *Environ* 409, 4048-4053.
- 124 Dodoo, D., Essumang, D., Jonathan, J., 2013. Accumulation profile and seasonal variations
125 of polychlorinated biphenyls (PCBs) in Bivalves *Crassostrea tulipa* (oysters) and
126 *Anadara senilis* (mussels) at three different aquatic habitats in two seasons in Ghana.
127 *Ecotox Environ Safe* 88, 26-34.
- 128 Dodoo, D., Essumang, D., Jonathan, J., Bentum, J., 2012. Polychlorinated biphenyls in
129 coastal tropical ecosystems: distribution, fate and risk assessment. *Environ Res* 118,
130 16-24.
- 131 EPA-Ghana, 1994. Environmental Protection Agency Act, 1994 Act 490, Ghana.
- 132 EPA-Ghana, 2007. National Implementation Plan of Stockholm Convention on Persistent
133 Organic Pollutants. Environmental Protection Agency, Accra, Ghana.
- 134 EPA-Ghana, 2016. Hazardous and Electronic Waste Control and Management Act, Act 917,
135 Environmental Protection Agency, Accra, Ghana.
- 136 EPA-Ghana, 2018. National Implementation Plan of the Stockholm Convention on Persistent
137 Organic Pollutants (2018 Revised Edition), Environmental Protection Agency, Accra,
138 Ghana.
- 139 Essumang, D.K., Eshun, A., Hogarh, J.N., Bentum, J.K., Adjei, J.K., Negishi, J., Nakamichi,
140 S., Habibullah-Al-Mamun, M., Masunaga, S., 2017. Perfluoroalkyl acids (PFAAs) in
141 the Pra and Kakum river basins and associated tap water in Ghana. *Sci Total Environ*
142 579, 729-735.
- 143 Esteban, M., Castaño, A., 2009. Non-invasive matrices in human biomonitoring: a review.
144 *Environ Int* 35, 438-449.
- 145 European Commission, 2006a. Setting Maximum Levels for Certain Contaminants in
146 Foodstuffs COMMISSION REGULATION (EC) No 1881/2006, Official Journal of
147 the European Union.

- 148 European Commission, 2006b. COMMISSION DIRECTIVE 2006/125/EC of 5 December
149 2006 on processed cereal-based foods and baby foods for infants and young children.
- 150 European Commission, 2011. COMMISSION REGULATION (EU) No 1259/2011 of 2
151 December 2011 amending Regulation (EC) No 1881/2006 as regards maximum levels
152 for dioxins, dioxin-like PCBs and non dioxin-like PCBs in foodstuffs.
- 153 European Commission, 2013. DIRECTIVE 2013/39/EU OF THE EUROPEAN
154 PARLIAMENT AND OF THE COUNCIL of 12 August 2013 amending Directives
155 2000/60/EC and 2008/105/EC as regards priority substances in the field of water
156 policy.
- 157 European Commission, 2016. European Union Pesticides Database
158 <http://ec.europa.eu/food/plant/pesticides>.
- 159 Federal Ministry of Environment Nigeria, 2009. National Implementation Plan for the
160 Stockholm Convention on Persistent Organic Pollutants (POPS) Final Report, Federal
161 Ministry of Environment, Nigeria.
- 162 Fisk, A.T., Hobson, K.A., Norstrom, R.J., 2001. Influence of chemical and biological factors
163 on trophic transfer of persistent organic pollutants in the Northwater Polynya marine
164 food web. *Environ Sci Technol* 35, 732-738.
- 165 Food and Drug Administration, 1995. Pesticide Residues in Food and Feed - Enforcement
166 Criteria: Compliance Policy Guide.
- 167 Fosu-Mensah, B.Y., Okoffo, E.D., Darko, G., Gordon, C., 2016. Assessment of
168 organochlorine pesticide residues in soils and drinking water sources from cocoa
169 farms in Ghana. *SpringerPlus* 5, 1-13.
- 170 Fu, J., Zhou, Q., Liu, J., Liu, W., Wang, T., Zhang, Q., Jiang, G., 2008. High levels of heavy
171 metals in rice (*Oryza sativa* L.) from a typical e-waste recycling area in southeast
172 China and its potential risk to human health. *Chemosphere* 71, 1269-1275.
- 173 Fujimori, T., Itai, T., Goto, A., Asante, K.A., Otsuka, M., Takahashi, S., Tanabe, S., 2016.
174 Interplay of metals and bromine with dioxin-related compounds concentrated in e-
175 waste open burning soil from Agbogbloshie in Accra, Ghana. *Environ Pollut* 209,
176 155-163.
- 177 Garcia-Heras, M.S., Arroyo, B., Simmons, R.E., Camarero, P.R., Mateo, R., Mougeot, F.,
178 2018. Blood concentrations of PCBs and DDTs in an avian predator endemic to
179 southern Africa: associations with habitat, electrical transformers and diet. *Environ*
180 *Pollut* 232, 440-449.
- 181 Gbeddy, G., Yeboah, P., Carboo, D., Doamekpor, L., Afful, S., Nartey, V., Frimpong, S.,
182 Doyi, I., Glover, T., Egbi, C., 2012. Organochlorine pesticide residues in African
183 catfish muscle, Nile tilapia muscle and gills from the middle Volta basin, Kpando
184 Torkor, Ghana and their potential health risks to humans. *Elixir Agric*, 9724-9730
- 185
- 186 Gioia, R., Akindele, A.J., Adebusoye, S.A., Asante, K.A., Tanabe, S., Buekens, A., Sasco,
187 A.J., 2014. Polychlorinated biphenyls (PCBs) in Africa: a review of environmental
188 levels. *Environ Sci Pollut Res Int* 21, 6278-6289.
- 189 Gioia, R., Eckhardt, S., Breivik, K., Jaward, F.M., Prieto, A., Nizzetto, L., Jones, K.C., 2011.
190 Evidence for major emissions of PCBs in the west African region. *Environ Sci*
191 *Technol* 45, 1349-1355.
- 192 Gunther, A.J., Davis, J.A., Hardin, D.D., Gold, J., Bell, D., Crick, J.R., Scelfo, G.M.,
193 Sericano, J., Stephenson, M., 1999. Long-term bioaccumulation monitoring with
194 transplanted bivalves in the San Francisco estuary. *Mar Pollut Bull* 38, 170-181.

- 195 Hanssen, L., Röllin, H., Odland, J.Ø., Moe, M.K., Sandanger, T.M., 2010. Perfluorinated
196 compounds in maternal serum and cord blood from selected areas of south Africa:
197 results of a pilot study. *J Environ Monit* 12, 1355-1361.
- 198 Harner, T., Shoeib, M., Diamond, M., Stern, G., Rosenberg, B., 2004. Using passive air
199 samplers to assess urban-rural trends for persistent organic pollutants. 1.
200 Polychlorinated biphenyls and organochlorine pesticides. *Environ Sci Technol* 38,
201 4474-4483.
- 202 Hassan, Y., Shoeib, T., 2015. Levels of polybrominated diphenyl ethers and novel flame
203 retardants in microenvironment dust from Egypt: an assessment of human exposure.
204 *Sci Total Environ* 505, 47-55.
- 205 Herrman, J.L., 1993. The Role of the World Health Organization in the evaluation of
206 pesticides. *Reg Toxicol Pharmacology* 17, 282-286.
- 207 Hites, R.A., Foran, J.A., Carpenter, D.O., Hamilton, M.C., Knuth, B.A., Schwager, S.J.,
208 2004. Global assessment of organic contaminants in farmed salmon. *Science* 303,
209 226-229.
- 210 Hogarh, J., Seike, N., Kobara, Y., Ofosu-Budu, G., Carboo, D., Masunaga, S., 2014.
211 Atmospheric burden of organochlorine pesticides in Ghana. *Chemosphere* 102, 1-5.
- 212 Hogarh, J.N., Seike, N., Kobara, Y., Masunaga, S., 2012. Atmospheric polychlorinated
213 naphthalenes in Ghana. *Environ Sci Technol* 46, 2600-2606.
- 214 Hosoda, J., Ofosu-Anim, J., Sabi, E.B., Akita, L.G., Onwona-Agyeman, S., Yamashita, R.,
215 Takada, H., 2014. Monitoring of organic micropollutants in Ghana by combination of
216 pellet watch with sediment analysis: e-waste as a source of PCBs. *Mar Pollut Bull* 86,
217 575-581.
- 218 Ilyina, T.P., 2007. The fate of persistent organic pollutants in the north sea: multiple year
219 model simulations of g-HCH, a-HCH and PCB 153. Springer Berlin Heidelberg.
- 220 Jacobs, M.N., Covaci, A., Schepens, P., 2002. Investigation of selected persistent organic
221 pollutants in farmed atlantic salmon (*Salmo salar*), salmon aquaculture feed, and fish
222 oil components of the feed. *Environ Sci Technol* 36, 2797-2805.
- 223 John, S.K., Fianko, J., Adu-Kumi, S., Pwamang, J., Serfoh-Armah, Y., Buah-Kwofie, A.,
224 Amoako, D., 2014. Contaminated site investigation for total PCBs in four temporary
225 transformer storage sites in Ghana. *Int J Sci Technol* 2, 141.
- 226 Jones, K.C., 1994. Observations on long-term air-soil exchange of organic contaminants.
227 *Environ Sci Pollut Res* 1, 172-177.
- 228 Jones, K.C., De Voogt, P., 1999. Persistent organic pollutants (POPs): state of the science.
229 *Environ Pollut* 100, 209-221.
- 230 Jozef M. Pacyna, T.F.B.F.W., 2000. Assessment of the Sources, Atmospheric Fluxes,
231 Environmental Cycling, Effects and Sinks of Persistent Organic Pollutants, POPs: An
232 International Workshop Held in Preston UK, April 30-May 1, 1998. Nordic Council
233 of Ministers.
- 234 Klanova, J., Čupr, P., Holoubek, I., Borůvková, J., Příbylová, P., Kareš, R., Tomšej, T.,
235 Ocelka, T., 2009. Monitoring of persistent organic pollutants in Africa. Part 1: passive
236 air sampling across the continent in 2008. *J Environ Monit* 11, 1952-1963.
- 237 Kunisue, T., Someya, M., Kayama, F., Jin, Y., Tanabe, S., 2004. Persistent organochlorines
238 in human breast milk collected from primiparae in Dalian and Shenyang, China.
239 *Environ Pollut* 131, 381-392.
- 240 Kuranchie-Mensah, H., Atiemo, S.M., Palm, L.M.N.-D., Blankson-Arthur, S., Tutu, A.O.,
241 Fosu, P., 2012. Determination of organochlorine pesticide residue in sediment and
242 water from the Densu river basin, Ghana. *Chemosphere* 86, 286-292.
- 243 Kuranchie-Mensah, H., Palm, L.M.N.-D., Manukure, S.A., Afful, S., Adjei-Martey, G.,
244 Arthur, J.K., 2011. Assessment of organochlorine pesticides and polychlorinated

- 245 biphenyls levels in fishes from the Volta Lake, Ghana and their suitability for human
246 consumption. *Elixir Food Sci* 41, 5982-5990.
- 247 Kuranchie-Mensah, H., Yeboah, P.O., Nyarko, E., Golow, A.A., 2013. Studies on
248 organochlorine pesticide residue in fishes from the Densu river basin, Ghana. *Bull*
249 *Environ Contam Toxicol* 90, 421-426.
- 250 L'Environnement et au Tourisme Guinée, 2012. PLAN NATIONAL DE MISE EN ŒUVRE
251 DE LA CONVENTION DE STOCKHOLM SUR LES POLLUANTS
252 ORGANIQUES PERSISTANTS.
- 253 Leung, A.O., Duzgoren-Aydin, N.S., Cheung, K., Wong, M.H., 2008. Heavy metals
254 concentrations of surface dust from e-waste recycling and its human health
255 implications in southeast China. *Environ Sci Technol* 42, 2674-2680.
- 256 Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gøtzsche, P.C., Ioannidis, J.P., Clarke,
257 M., Devereaux, P.J., Kleijnen, J., Moher, D., 2009. The PRISMA statement for
258 reporting systematic reviews and meta-analyses of studies that evaluate health care
259 interventions: explanation and elaboration. *PLoS Medicine* 6, e1000100.
- 260 Liem, A.K.D., Furst, P., Rappe, C., 2000. Exposure of populations to dioxins and related
261 compounds. *Food Add Contam* 17, 241-259.
- 262 Marvin, C., Alae, M., Painter, S., Charlton, M., Kauss, P., Kolic, T., MacPherson, K.,
263 Takeuchi, D., Reiner, E., 2002. Persistent organic pollutants in Detroit river
264 suspended sediments: polychlorinated dibenzo-p-dioxins and dibenzofurans, dioxin-
265 like polychlorinated diphenyls and polychlorinated naphthalenes. *Chemosphere* 49,
266 111-120.
- 267 Mateo, R., Lacorte, S., Taggart, M.A., 2016. An Overview of Recent Trends in Wildlife
268 Ecotoxicology, *Current Trends in Wildlife Res.* Springer, pp. 125-150.
- 269 Meng, X.Z., Zeng, E.Y., Yu, L.P., Mai, B.X., Luo, X.J., Ran, Y., 2007. Persistent
270 halogenated hydrocarbons in consumer fish of China: regional and global implications
271 for human exposure. *Environ Sci Technol* 41, 1821-1827.
- 272 MINISTERE DE L'ENVIRONNEMENT ET DU CADRE DE VIE, 2007. PLAN
273 NATIONAL DE MISE EN ŒUVRE DE LA CONVENTION DE STOCKHOLM
274 SUR LES POLLUANTS ORGANIQUES PERSISTANTS (POPs).
- 275 Moeckel, C., Nizzetto, L., Guardo, A.D., Steinnes, E., Freppaz, M., Filippa, G., Camporini,
276 P., Benner, J., Jones, K.C., 2008. Persistent organic pollutants in boreal and montane
277 soil profiles: distribution, evidence of processes and implications for global cycling.
278 *Environ Sci Technol* 42, 8374-8380.
- 279 Nieuwoudt, C., Quinn, L.P., Pieters, R., Jordaan, I., Visser, M., Kylin, H., Borgen, A.R.,
280 Giesy, J.P., Bouwman, H., 2009. Dioxin-like chemicals in soil and sediment from
281 residential and industrial areas in central South Africa. *Chemosphere* 76, 774-783.
- 282 Ntow, W.J., 2001. Organochlorine pesticides in water, sediment, crops, and human fluids in
283 a farming community in Ghana. *Arch Environ Con Tox* 40, 557-563.
- 284 Ntow, W.J., 2005. Pesticide residues in Volta Lake, Ghana. *Lakes & Reservoirs: Res Manag*
285 10, 243-248.
- 286 Ntow, W.J., Ameyibor, J., Kelderman, P., Drechsel, P., Gijzen, H.J., 2007. Dissipation of
287 endosulfan in field-grown tomato (*Lycopersicon esculentum*) and cropped soil at
288 Akumadan, Ghana. *J Agric Food Chem* 55, 10864-10871.
- 289 Ntow, W.J., Drechsel, P., Botwe, B.O., Kelderman, P., Gijzen, H.J., 2008a. The impact of
290 agricultural runoff on the quality of two streams in vegetable farm areas in Ghana. *J*
291 *Environ Qual* 37, 696-703.
- 292 Ntow, W.J., Kelderman, P., Drechsel, P., Carboo, D., Nartey, V., Gijzen, H.J., 2011.
293 Pesticide residues contamination of vegetables and their public health implications in
294 Ghana. *J Environ Issues Agric in Developing Countries* 3, 10-18.

- 295 Ntow, W.J., Tagoe, L.M., Drechsel, P., Kelderman, P., Gijzen, H.J., Nyarko, E., 2008b.
296 Accumulation of persistent organochlorine contaminants in milk and serum of farmers
297 from Ghana. *Environ Res* 106, 17-26.
- 298 Okoffo, E.D., Fosu-Mensah, B.Y., Gordon, C., 2016. Persistent organochlorine pesticide
299 residues in cocoa beans from Ghana, a concern for public health. *Int J Food Contam*
300 3, 5.
- 301 Osibanjo, O., Bouwman, H., Bashir, N., Okond'Ahoka, J., Choong Kwet Yve, R., Onyoyo,
302 H., 2002. Regionally based assessment of persistent toxic substances. Sub-saharan
303 Africa regional report. UNEP Chemicals, Geneva.
- 304 Otchere, F.A., 2005. Organochlorines (PCBs and pesticides) in the bivalves *Anadara* (*Senilis*)
305 *senilis*, *Crassostrea tulipa* and *Perna perna* from the lagoons of Ghana. *Sci Total*
306 *Environ* 348, 102-114.
- 307 Oteng-Ababio, M., 2012. The role of the informal sector in solid waste management in the
308 GAMA, Ghana: challenges and opportunities. *Tijdschrift voor economische en*
309 *sociale geografie* 103, 412-425.
- 310 Oteng-Ababio, M., Amankwaa, E.F., Chama, M.A., 2014a. The local contours of scavenging
311 for e-waste and higher-valued constituent parts in Accra, Ghana. *Habitat Int* 43, 163-
312 171.
- 313 Oteng-Ababio, M., Chama, M.A., Amankwaa, E.F., 2014b. Qualitative analysis of the
314 presence of PBDE in ashes, soils and vegetables from Agbogboshie e-waste
315 recycling site. *J Environ Res Manag* 5.
- 316 Owusu-Boateng, G., Amuzu, K.K., 2013. Levels of organochlorine pesticides residue in
317 cabbage cultivated in farms along river Oyansia, Accra-Ghana. *Am J Sci Ind Res* 4,
318 489-498.
- 319 Patterson, J., Donald G, Wong, L.Y., Turner, W.E., Caudill, S.P., DiPietro, E.S., McClure,
320 P.C., Cash, T.P., Osterloh, J.D., Pirkle, J.L., Sampson, E.J., Needham, L.L., 2009.
321 Levels in the US population of those persistent organic pollutants (2003– 2004)
322 included in the Stockholm Convention or in other long-range transboundary air
323 pollution agreements. *Environ Sci Technol* 43, 1211-1218.
- 324 Pozo, K., Harner, T., Lee, S.C., Wania, F., Muir, D.C.G., Jones, K.C., 2009. Seasonally
325 resolved concentrations of persistent organic pollutants in the global atmosphere from
326 the first year of the GAPS study. *Environ Sci Technol* 43, 796-803.
- 327 Pozo, K., Harner, T., Wania, F., Muir, D.C., Jones, K.C., Barrie, L.A., 2006. Toward a global
328 network for persistent organic pollutants in air: results from the GAPS study. *Environ*
329 *Sci Technol* 40, 4867-4873.
- 330 Quansah, R., Bend, J.R., Abdul-Rahaman, A., Armah, F.A., Luginaah, I., Essumang, D.K.,
331 Iddi, S., Chevrier, J., Cobbina, S.J., Nketiah-Amponsah, E., 2016. Associations
332 between pesticide use and respiratory symptoms: a cross-sectional study in southern
333 Ghana. *Environ Res* 150, 245-254.
- 334 Rotterdam Convention Secretariat, 2003. The Rotterdam Convention, UNEP, Retrieved from:
335 <http://www.pic.int/> [Accessed on: 10th July 2017].
- 336 Ryan, P.G., Bouwman, H., Moloney, C.L., Yuyama, M., Takada, H., 2012. Long-term
337 decreases in persistent organic pollutants in South African coastal waters detected
338 from beached polyethylene pellets. *Mar Pollut Bull* 64, 2756-2760.
- 339 Schecter, A., Pavuk, M., Päpke, O., Ryan, J.J., Birnbaum, L., Rosen, R., 2003.
340 Polybrominated diphenyl ethers (PBDEs) in US mothers' milk. *Environ Health Persp*
341 111, 1723-1729.
- 342 Schulz, R., Peall, S.K., 2001. Effectiveness of a constructed wetland for retention of
343 nonpoint-source pesticide pollution in the Lourens river catchment, South Africa.
344 *Environ Sci Technol* 35, 422-426.

- 345 Sjodin, A., Wong, L.Y., Jones, R.S., Park, A., Zhang, Y., Hodge, C., DiPietro, E., McClure,
346 C., Turner, W., Needham, L.L., Patterson, D.G., 2008. Serum concentrations of
347 polybrominated diphenyl ethers (PBDEs) and polybrominated diphenyl (PBB) in the
348 United States population: 2003-2004. *Environ Sci Technol* 42, 1377-1384.
- 349 Stockholm Convention Secretariat, 2001. Stockholm Convention on Persistent Organic
350 Pollutants <http://chm.pops.int/> [Accessed on: 19th September, 2017], UNEP.
- 351 Strandberg, B., Dodder, N.G., Basu, I., Hites, R.A., 2001. Concentrations and spatial
352 variations of polybrominated diphenyl ethers and other organohalogen compounds in
353 Great Lakes air. *Environ Sci Technol* 35, 1078-1083.
- 354 Tanabe, S., Kunisue, T., 2007. Persistent organic pollutants in human breast milk from Asian
355 countries. *Environ Pollut* 146, 400-413.
- 356 Thomas, G.O., Wilkinson, M., Hodson, S., Jones, K.C., 2006. Organohalogen chemicals in
357 human blood from the United Kingdom. *Environ Pollut* 141, 30-41.
- 358 Tue, N.M., Goto, A., Takahashi, S., Itai, T., Asante, K.A., Kunisue, T., Tanabe, S., 2016.
359 Release of chlorinated, brominated and mixed halogenated dioxin-related compounds
360 to soils from open burning of e-waste in Agbogboshie (Accra, Ghana). *J Hazard*
361 *Mater* 302, 151-157.
- 362 Tutu, A.O., Yeboah, P.O., Golow, A.A., Adu-Kumi, S., Clarke, E., Osei-Fosu, P., 2013.
363 Levels of organochlorine pesticide residues found in the breast milk of some first-
364 birth mothers from a rural community (Ada) in Ghana. *Elixir Pollut*, 12668-12672.
- 365 USDA, 2011. Pesticide Data Program: Annual Summary, Calendar Year 2009.
- 366 USEPA, 1989. Integrated Risk Information System on Polychlorinated Biphenyls. National
367 Center for Environmental Assessment, Office of Research and Development,
368 Washington, DC.
- 369 USEPA, 2000. Guidance for Assessing Chemical Contaminant Data for Use in Fish
370 Advisories: Volume 2 Risk Assessment and Fish Consumption Limits Third Edition.
- 371 USEPA, 2008a. Integrated Risk Information System on 2,2',4,4',5-Pentabromodiphenyl ether
372 (BDE-99)
373 https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/1008_summary.pdf
- 374 USEPA, 2008b. Integrated Risk Information System on 2,2',4,4',5,5'-Hexabromodiphenyl
375 ether (BDE-153)
376 https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/1009_summary.pdf
- 377 USEPA, 2008c. Integrated Risk Information System on 2,2',4,4'-Tetrabromodiphenyl ether
378 (BDE-47)
379 https://cfpub.epa.gov/ncea/iris/iris_documents/documents/subst/1010_summary.pdf.
- 380 USEPA, 2009. Ground Water and Drinking Water: National Primary Drinking Water
381 Regulations.
- 382 USEPA, 2016. Drinking Water Health Advisory for Perfluorooctanoic Acid (PFOA).
- 383 Vallack, H.W., Bakker, D.J., Brandt, I., Broström-Lundén, E., Brouwer, A., Bull, K.R.,
384 Gough, C., Guardans, R., Holoubek, I., Jansson, B., 1998. Controlling persistent
385 organic pollutants—what next? *Environ Toxicol Pharmacol* 6, 143-175.
- 386 van den Berg, M., Kypke, K., Kotz, A., Tritscher, A., Lee, S.Y., Magulova, K., Fiedler, H.,
387 Malisch, R., 2017. WHO (2001) DDT (Addendum). World Health Organization,
388 Geneva, In: WHO/UNEP global surveys of PCDDs, PCDFs, PCBs and DDTs in
389 human milk and benefit-risk evaluation of breastfeeding. *Arch Toxicol* 91, 83-96.
- 390 Van Metre, P.C., Mahler, B.J., 2005. Trends in hydrophobic organic contaminants in urban
391 and reference lake sediments across the United States, 1970– 2001. *Environ Sci*
392 *Technol* 39, 5567-5574.
- 393 van Wyk, E., Bouwman, H., van der Bank, H., Verdoorn, G.H., Hofmann, D., 2001.
394 Persistent organochlorine pesticides detected in blood and tissue samples of vultures

- 395 from different localities in South Africa. *Comp Biochem Physiol Part C: Toxicol*
396 *Pharmacol* 129, 243-264.
- 397 White, R., 2008. Toxic cities: globalizing the problem of waste. *Social Justice* 35, 107-119.
- 398 WHO, 2000. Air Quality Guideline for Europe. Copenhagen, WHO Regional Office for
399 Europe.
- 400 WHO, 2001. Concise International Chemical Assessment Document 34: Chlorinated
401 Napthalenes, Geneva.
- 402 WHO, 2006. Protecting Groundwater for Health: Managing the Quality of Drinking-water
403 Sources.
- 404 WHO, 2017. Guidelines for Drinking-water Quality, 4th Edition.
- 405 Willett, K.L., Ulrich, E.M., Hites, R.A., 1998. Differential toxicity and environmental fates of
406 hexachlorocyclohexane isomers. *Environ Sci Technol* 32, 2197-2207.
- 407 Wittsiepe, J., Fobil, J.N., Till, H., Burchard, G.-D., Wilhelm, M., Feldt, T., 2015. Levels of
408 polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/Fs) and biphenyls (PCBs)
409 in blood of informal e-waste recycling workers from Agbogbloshie, Ghana, and
410 controls. *Environ Int* 79, 65-73.
- 411 Zhang, G., Parker, A., House, A., Mai, B., Li, X., Kang, Y., Wang, Z., 2002. Sedimentary
412 records of DDT and HCH in the Pearl River Delta, South China. *Environ Sci Technol*
413 36, 3671-3677.
- 414

Highlights on Review Article:

1. Current status of POPs in Ghana is reviewed.
2. Health risks from PCDD/Fs at e-waste sites.
3. High health risk from exposure to PFASs and DDT related compounds in drinking water.
4. Large data gaps identified.
5. Future perspectives to include understudied POPs.