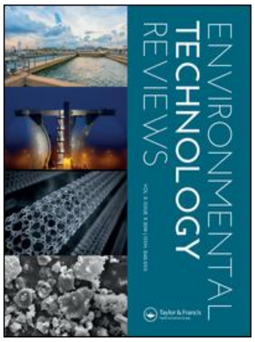

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Review

E-waste recycling and public exposure to organic compounds in developing countries: a review of recycling practices and toxicity levels in Ghana

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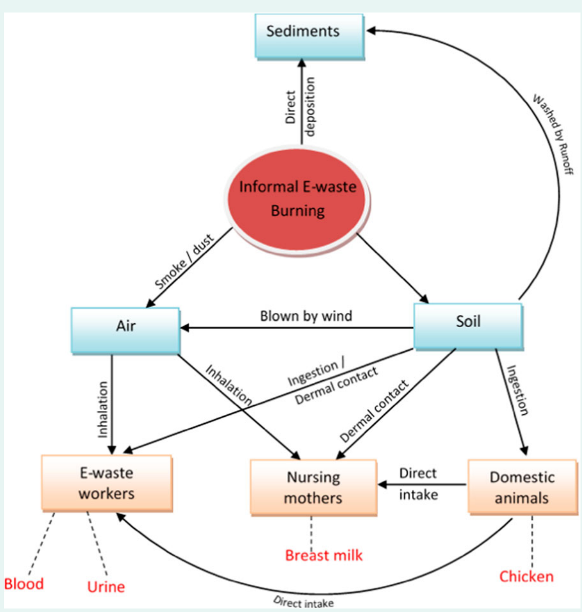
ABSTRACT

This paper reviews e-waste practices and aggregates the toxicity levels of organic compounds in different environmental media and human body fluids resulting from e-waste recycling activities in Ghana. Literature was searched from three academic databases (Science Direct, SpringerLink and PUBMED). Research articles published in English from 2010 to 2018 were selected in addition to reports of country studies. In all, 13 documents passed the inclusion criteria. E-waste recycling practices in Ghana were found to be mainly rudimentary. The major organic contaminants found in soils, air, sediments, food and body fluids of people exposed to e-waste recycling activities are PAHs, PCBs, Dioxin-like PCBs, PCDD/Fs, PBDD/Fs and PBDEs. The concentration of PCBs in the blood of e-waste workers and breast milk of nursing mothers at the recycling areas were respectively 0.082 µg/g (blood) and 3.64 ng/g lipid wt (breast milk). PAH was 3.94 µg/g creatinine in the urine of e-waste workers and 4,822 ng/g (median) in the soils at open burning areas. PCDD/F was 12.1 pg/g lipid base WHO_{2005}-TEQ per year in the blood of e-waste workers and 988 pg TEQ/g in sediments of a shallow lagoon near the largest e-waste recycling site. Further studies are required to establish the levels of organic contaminants in air, water and foodstuffs at e-waste recycling sites and body burdens of children living or illegally working at e-waste recycling sites.



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Introduction

Globally, different types of wastes with different characteristics are produced daily from domestic and industrial activities which require proper management. One major category which has generated much interest and concerns among environmentalists

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is electronic waste (e-waste). By strict definition, e-waste 'describes waste electronic goods such as computers, televevisions and cell phones' [1]. However, the term is often used interchangeably with the term WEEE (waste electrical and electronic equipment). An example of this usage is seen in the definition adopted by the 'Solve the E-waste Problem' (Step) Initiative in which e-waste is defined as 'all items of *electrical and electronic* equipment (EEE) and its parts that have been discarded by its owner as waste without the intent of re-use' [2]. On the other hand, Robinson [1] restricts the use of the term e-waste to only electronic waste while defining WEEE to include 'traditionally non-electronic goods such as refrigerators and ovens'. In this paper, however, the term e-waste is used as in Step Initiative [2] to comprise both electronic and electrical waste.

The rate of global e-waste generation keeps increasing yearly with most originating from Asia [3]. It has been reported that the global e-waste generation increased from 33.8 million metric tons in the year 2010 (equivalent to 5.0 kg per inhabitant) to 44.7 million metric tons in 2016 (equivalent to 6.1 kg per inhabitant) and is expected to increase to 52.2 million metric tons (equivalent to 6.8 kg per inhabitant) in 2021 [3]. Although Africa contributes less than 5% of the global annual e-waste generation [3], an estimated 75–80% of the e-waste generated worldwide is transported to Africa for reuse, recycling, or disposal [4, 5].

Available data on e-waste flow to developing countries is inconsistent due to the difficulty of tracking the movement of e-waste. This may be further attributed to the high volume of e-waste generation and import, mislabelling of e-waste during import and export and the informal collection and recycling practices. This notwithstanding, about 150,500 tonnes of second-hand EEE were imported into Ghana in 2009, from which 15% were e-waste on arrival [6]. The imported second-hand EEE included used refrigerators and air-conditioners which are banned under the Energy Efficiency Regulations, 2008 (LI 1932). In an attempt to control the proliferation of e-waste in the country, recent regulations prohibit the import and export of WEEE and impose an advanced eco-levy on importers and manufacturers of new and used EEE [7].

Ghana's e-waste recycling chain is dominated by the informal sector which accounts for about 95% coverage [8].. The informal e-waste recycling activities is fuelled by the massive importation of second-hand EEE. Even though the processes used by the informal sector are rudimentary, unsound and often illegal, they handle a larger proportion of the e-waste stream. Between 2010 and 2014, about 110,000 tonnes of e-waste were recycled in Ghana [4]. Economic incentives drive the activities of informal e-waste workers, with over 20,000 people estimated to be employed directly in the refurbishing and recycling sector [4]. The income obtained by the e-waste workers supports over 121,000 people and generates US$105–268 million annually to the economy of Ghana [9].

E-waste is a source of valuable metals (copper, platinum, gold) as well as hazardous heavy metals (especially lead, antimony, mercury, cadmium, nickel), polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) [1]. Many of the hazardous chemicals and materials from e-waste enter the environment through the informal recycling of the e-waste. The toxins released from improper e-waste recycling activities are heterogeneous, mostly persistent with long-term (chronic) exposure. Primary and secondary e-waste workers and people residing around e-waste recycling sites are continuously or repeatedly exposed to the toxins over long period of time.

Many exposure studies associated with informal recycling practices in developing countries have been conducted [10, 11, 12, 13, 14]. Studies have sought to determine e-waste contaminant levels in primary e-waste workers (dismantlers, recyclers, etc.) [15, 16], secondary e-waste workers, i.e. people who do business with or provide services to the primary e-waste recycling workers such as food, water and beverage sellers, etc [17] and nursing mothers living or working close to the e-waste recycling sites [18, 19]. Elevated levels of hazardous metals, essential elements and organic compounds in the blood, urine [20, 21], hair of e-waste workers [22] and environmental media (soil, water, and air) [23] have been documented. Burning e-waste may generate dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), polyhalogenated aromatic hydrocarbons (PHAHs), and hydrogen chloride [1]. Airborne and dust-borne contaminants also threaten the health of people who reside or work close to e-waste recycling sites [24]. However, to the best of our knowledge, there is no synthesis of research findings on organic contaminants resulting from e-waste recycling activities in Ghana where the Agbogbloshie recycling site has gained an international notoriety as one of the world's leading e-waste recycling hub [25, 26, 27]. This paper reviews e-waste practices in Ghana and aggregates the toxicity levels of organic compounds in different environmental media and humans, resulting from e-waste activities in Ghana. Particular emphasis is laid on the recycling site at Agbogbloshie, an urban slum in the capital, Accra. To better appreciate the extent of pollution, the levels of organic compounds are compared with national and international guideline values.

Approach to the review

The review focussed on the recycling practices employed in developing countries and narrowed down to Ghana to examine the toxicity levels of e-waste-related organic compounds in various environmental media and humans in the country. Literature for this review were retrieved through a systematic and extensive search among peer-reviewed papers published in English from 1 January 2010 to 31 December 2018. The electronic databases considered were ScienceDirect, SpringerLink and PUBMED. The choice of these databases was influenced by institutional access. For the first part of this paper, which reports e-waste recycling practices in developing countries, all documents (original articles, reviews, book chapters, and conference papers) were included in the search. The search was refined for e-waste recycling practices relating to developing countries.

For the second part of the paper reporting toxicity levels in Ghana, search terms used included (e-waste OR electronic waste OR WEEE) AND (PAH OR PCB OR POP OR Organic Compound) AND (Ghana OR Agbogbloshie). Broad search terms were used to ensure that, as much as possible, no publication was overlooked. Only original research articles were reviewed, all other documents were excluded. The reference lists of included studies were assessed for other relevant studies. From the primary results of this search, other related literature were identified. To supplement the academic articles, reports published on the websites of Greenpeace International (a non-governmental environmental organization) and the Basel Convention were reviewed. Papers that did not report human and environmental exposure to organic compounds from e-waste recycling were excluded. All papers from the three databases were combined and scrutinized for duplications. From the search, 177 papers were obtained but 155 were excluded based on the criteria stated above and 9 were removed for duplication. Figure 1 shows the methodology for selecting documents for this review.

It is emphasized that, not many studies were found on the sources and exposure pathways of the e-waste contaminants in Ghana. Therefore, to make the reader appreciate the connection between the e-waste recycling practices and the reported toxicity levels in the various environmental media and human body fluids, the review of the case of Ghana is preceded by a general review of e-waste contaminant sources and exposure pathways.

E-waste contaminant sources and exposure pathways

Sources of e-waste-related organic compounds

Organic contaminants from e-waste recycling activities occur as either components of EEE or formed from the burning of e-waste components. Polybrominated diphenyl ethers (PBDEs) (including many different congeners), phthalates diesters, PCBs and chlorinated benzenes [28, 29] are used in the manufacture of electrical and electronic equipment. Aside their presence in EEE components, PCBs, PAHs and PCDD/Fs are formed from the incomplete combustion of chlorinated or brominated organic compounds [30, 31, 32, 33, 34, 35, 36] under low or no oxygen conditions [37].

Using molecular diagnostic ratios, total index (TI) and compositional profiles, Daso et al. [30] found PAHs at the Agbogbloshie site to originate from high temperature burning of e-waste using discarded car tyres, spent oil and plastics (petrogenic and pyrogenic sources). Pyrogenic formation of PAHs occurs at a temperature of 100°C–1200°C [37]. These temperature ranges are created and maintained during the combustion of e-waste to recover precious materials. PCBs found at the e-waste recycling site was attributed to the disposal of obsolete transformer components and capacitors. PCBs are used in transformer oils, capacitor dielectrics and flame-retardant plasticizers [38, 36]. PDBEs and TPPs are used as flame retardant in plastics and foams [39]. Phthalate

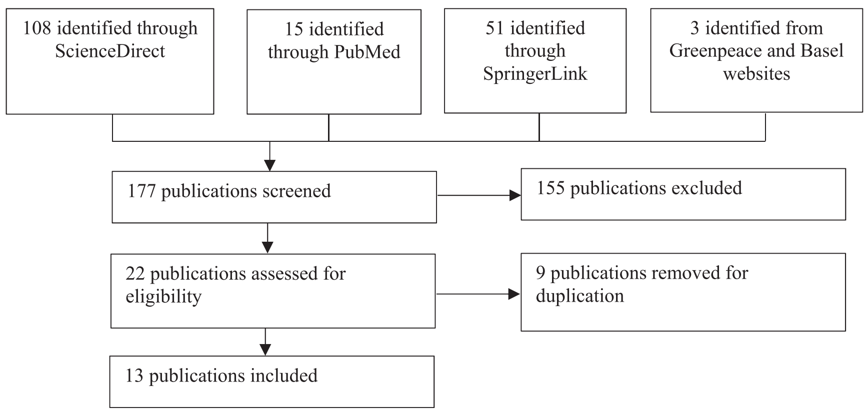

Figure 1. Methodology for selecting documents for review.

diesters are also used as plasticizers in coated wires and cables [28].

Acute (short term) exposure to PAH by humans leads to eye and skin irritation, nausea, vomiting, diarrhoea [40] and impaired liver function [41]. Chronic exposure in humans causes skin, lung, bladder and gastrointestinal cancers [42, 43], reduced immune function, cataracts, kidney and liver damage, breathing problems, and lung malfunction [37]. PCBs cause endocrine-disrupting activities, infertility, miscarriage [44, 45] and reduced sperm motility [46]. PCBs are also reported to cause cancer, low birth weight, low IQ, hypertension, diabetes and asthma [47]. Human exposure to PCDD/F causes lung cancer, female breast cancer and cardiovascular disease [48, 49]. Increased PBDEs in breast milk causes decreased birth weight and length in humans. Human health effects of exposure to low concentrations of PBDEs are thyroid hormone disruption, neurodevelopmental effects and, cancer (for some PBDE congeners) [50, 51].

E-waste recycling practices

The informal sector in developing countries such as Ghana recycles about 95% of the e-waste generated. The main e-waste recycled are discarded computers, monitors, TVs and printers. Recycling is performed by scavengers and dismantlers who use rudimentary recycling methods. Varying scales of informal recycling of e-waste have been reported in Ghana and other developing countries such as Bangladesh, Cambodia, China, India, Indonesia, Nepal, Nigeria, Pakistan, Philippines, Sri Lanka, Thailand and Vietnam [52, 53, 54, 55, 56, 57]. A process flow diagram for the informal

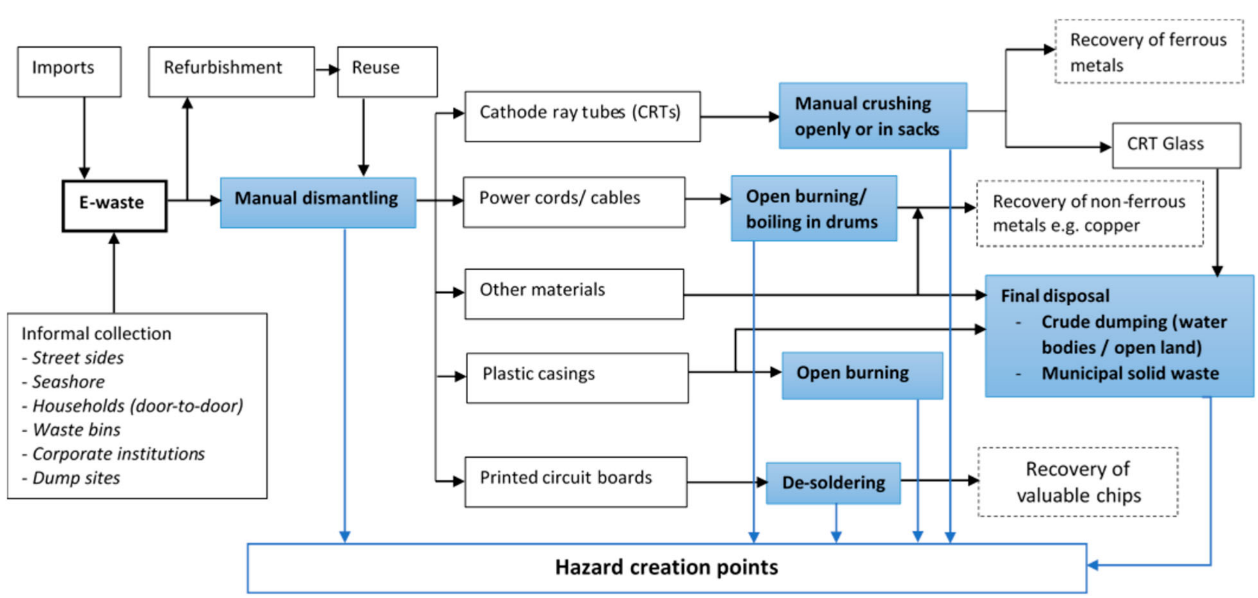

Figure 2. Process flow diagram for informal e-waste recycling practices in Ghana.

e-waste recycling practices in Ghana is presented in Figure 2. The recycling processes involve dismantling electronic and electrical devices with crude equipment such as chisels, hammers, pliers and screw drivers often without any personal protective equipment (PPE) [58]. Cathode ray tubes (CRT) are bashed open with hammers exposing the toxic phosphorus dust in them. In Indonesia, CRT are placed in sacks and crushed with hammer to minimize phosphorus emission into the surrounding environment [57].

Open burning of wires and cables (sometimes with attached printed circuit boards) is used to recover copper from their coatings. The open fires are set and sustained using polyurethane and discarded car tyres [59, 28]. The practice is quite different in Barangay, Indonesia, where cables are boiled in steel drums to enhance the removal of copper wires [57]. Even though the workers, in this case, are not directly exposed to the fumes from open burning, the wastewater from the boiling, if improperly managed, could pollute the environment. Valuable chips on circuit boards are de-soldered from printed circuit boards over coal grills, exposing the workers to fumes containing metal(loids) and organic compounds. Gold is recovered from chips and other e-waste components using acid baths. Though not practised in Ghana, acid leaching to recover precious metals like gold is extensively used in China, India, Nigeria and Pakistan [60, 61, 55, 62, 14]. In Malaysia, cyanide is used for leaching gold [63] due to the simplicity, economic benefit, minimal dosage requirement and alkaline operating conditions [64]. Improper treatment of wastewater containing acids and cyanide can affect human health and the environment.

Materials perceived to have no economic value are also burnt periodically to reduce their volume or dumped in river bodies/open lands [59, 29, 65, 56].

The major e-waste recycling centres

Apart from the notorious site at Agbogbloshie, pockets of e-waste recycling activities have been reported at other places in the Greater Accra metropolitan area, namely Ashaiman, Pantang [24] and Tema [6]. In Kumasi, the second largest city of Ghana, places that have been noted for e-waste recycling activities include Dagomba Line, Suame Magazine, Aboabo and Angola [66]. Beside these, other notable centres of e-waste recycling activities around the country are Koforidua [59, 28], Takoradi [66, 67] and Obuasi [66].

Due to its international recognition as a major informal e-waste recycling centre in the world, this section provides some highlights of the Agbogbloshie recycling site, which is located at longitude 05°35′N and latitude 00°06′W. The Agbogbloshie Township occupies an area of about 16 km^2 with about 40,000 people living and working at the e-waste site [68]. The Agbogbloshie recycling area is situated on a flat ground and bounded northwest by the Odaw River [6, 69, 70, 8]. The low-lying nature of the e-waste site makes it particularly prone to floods. A large informal settlement (called Old Fadama) lies adjacent to Agbogbloshie, southeast of the waste dump [71]. The Agbogbloshie site is surrounded by places of worship (a mosque and churches), residences, a police post, recreational facilities (an informal football pitch, a church-owned basketball court), and a goat/cattle pasture [24]. In terms of e-waste recycling activities, the site comprises mainly of an open burning area, personal computer and television repairers' shops, dismantling area, core burning and charring sites [68]. Figure 3 is a map of the Agbogbloshie e-waste recycling site in Ghana.

Exposure pathways to e-waste-related organic compounds

In general, people get exposed to organic compounds from e-waste through direct (primary) occupation in e-waste recycling or indirect (secondary) occupation that brings them to e-waste recycling sites to do business with the primary e-waste workers. Others also get exposed to e-waste-related contaminants due to their proximity to e-waste recycling sites by virtue of their places of residence, work or other reasons that may not necessarily be e-waste-related. It has been observed that aside the primary and secondary e-waste workers, other vulnerable groups are foetuses, children, pregnant women and elderly people who live within the vicinity of e-waste recycling sites. People who live or work in or close to e-waste recycling sites have longer exposure history and higher body burden [72].

Primarily, burning processes are responsible for the release of toxic substances from e-waste sources into the atmosphere, soils and water bodies. Subsequently, inhalation, ingestion and dermal contact become the

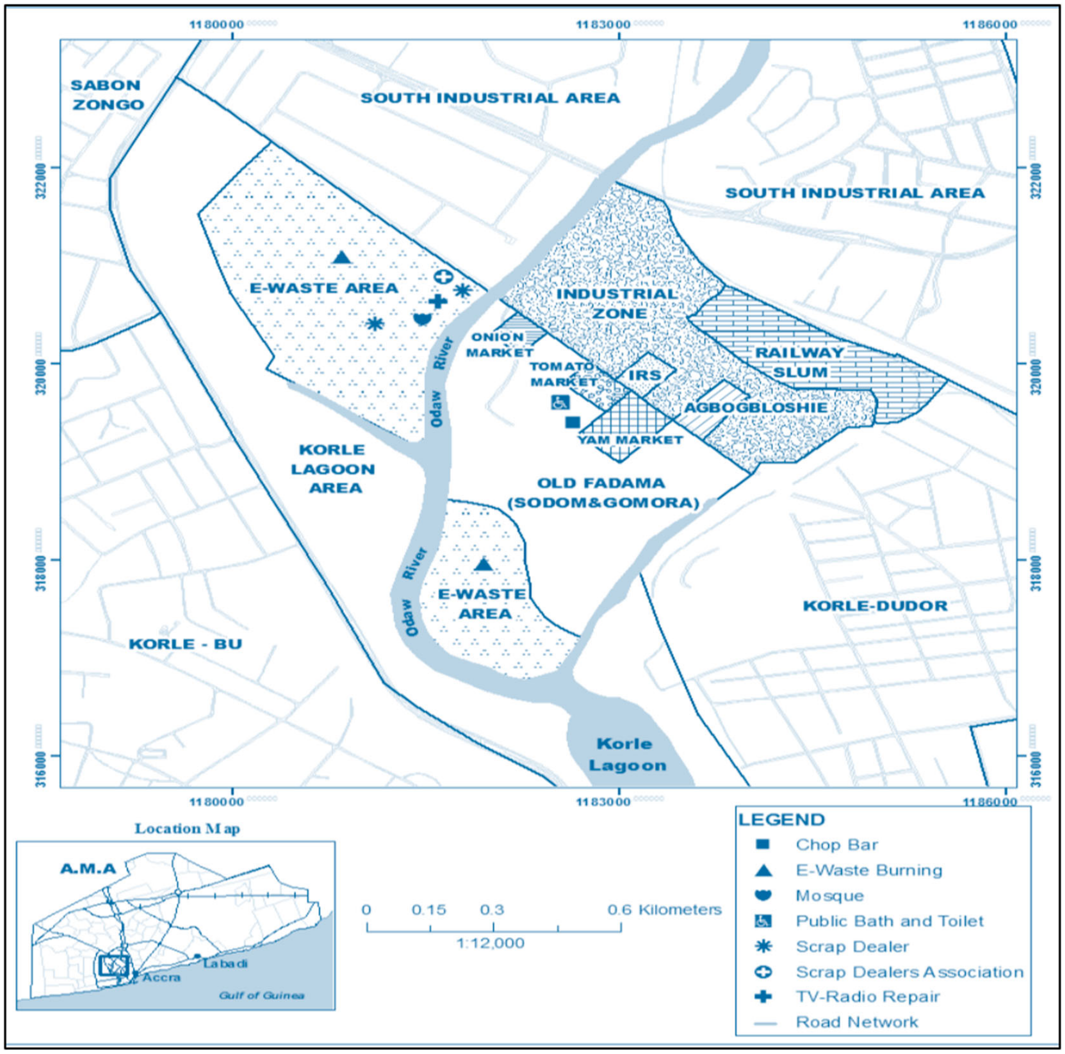

Figure 3. Map of the Agbogbloshie E-waste recycling site in Ghana [8].

main routes of human exposure to organic compounds from e-waste [73]. Thus, the commonest pathways are related to uptake or contact with contaminated soil, dust, air, water and food [74, 38, 75, 76, 77, 1]. Table 1 presents some organic contaminants from e-waste processing and their exposure pathways.

Figure 4 conceptualizes the multi-pathway release of organic compounds in different environmental compartments, which are discussed in detail in the subsequent sub-sections.

Water-related pathways

Organic contaminants from e-waste recycling are leached from dumpsites into aquatic environment or through atmospheric deposition. The presence of organic contaminants in the aquatic environment enhances their uptake by aquatic organisms and subsequently by humans. PAHs [74, 78], PBDEs [79], PCDD/Fs and PCBs [80] have low water solubility restricting their dissolution and exposure through

Table 1. Summary of exposure pathways of some e-waste-related hazardous chemicals.

Hazardous chemical	Source	Route of exposure
PBDEs	Fire retardants in thermoplastic components, cable insulation	Ingestion, inhalation, and transplacental
PCBs	Electrical transformers, capacitors, condensers, PVC;	Ingestion, inhalation or dermal contact, and transplacental
Dioxin-like PCBs (DL-PCBs)	Combustion by-product. Found in dielectric fluids, lubricants and coolants	Ingestion, inhalation, and dermal absorption
PCDD/Fs	Combustion by-product	Ingestion, inhalation, dermal contact, and transplacental
PAHs	Formed during combustion of product	Ingestion, inhalation, and dermal contact

Source: [52, 29, 137].

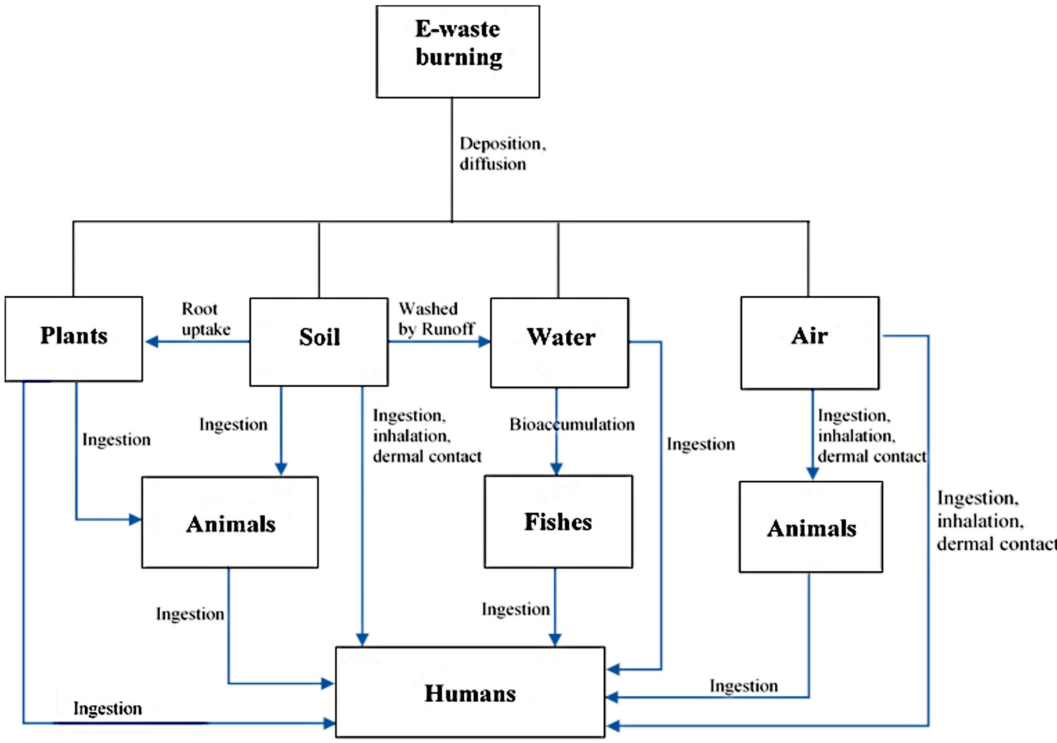

Figure 4. Multi-pathway of e-waste-related organic contaminants in different environmental compartments.

water. They are therefore absorbed onto sediments and bioaccumulate when taken up by aquatic organisms and subsequently by humans. Fishes may also take up organic compounds when water with contaminated sediments pass through their gills [79]. Humans are exposed to organic compounds in aquatic systems through the ingestion of contaminated fishes and their products [81]. The closeness of e-waste sites to water sources makes this exposure route important [6, 70, 8]. In China, Ghana and Nigeria, organic contaminants from e-waste processing sites have been found in sediments and aquatic species [82, 28, 83, 84].

Soil-related pathways

Plant roots can absorb some organic compounds (such as PBDEs) from soils and translocate them to other plant parts. Domestic animals (such as cattle, goats, sheep, fowls, etc.) and wildlife could be exposed through the uptake from soil and plants during grazing. Bioaccumulation coefficients of most organic compounds are small (<0.01), but their entry into the food chain is facilitated by plant uptake [1]. The high lipophilicity of PCBs causes them to be adsorbed strongly to soil and sediments which are ingested by bottom-feeding fish. Due to bioaccumulation, PCB in fishes can be about one million times higher than in the aquatic environment [75]. PCBs leach slowly from soils and insignificantly translocate to plants. PBDEs have been found in in-house and out-house food sources at e-waste recycling sites [85]. PBDEs are highly lipophilic so their concentration are lower in vegetables than other food samples with high lipid content [85]. PAH can be taken up by plants and subsequently translocated to other parts of the plant [37]. The intake of food contaminated with organic compounds by humans could present additional exposure pathway. A study by Zhao et al. [86] revealed elevated levels (approximately 2 times higher than the control) of PBDEs and PCBs in food (vegetables, rice, hen eggs, pork and chicken produced locally) obtained from local grocery stores from e-waste disassembling sites in Zhejiang, China. Fatty and sea foods are considered a major source of PCDD/Fs and PCBs [80]. Though there are no reported cases of direct human consumption of vegetation from the Agblogbloshie e-waste site, its proximity to cattle/goat pasture [24] and domestic fowls could be a possible route of exposure to organic compounds.

Air-and-dust-related pathways

Without direct contact with soils, contaminated dust particles from e-waste recycling sites are carried by air to human targets. In this sense, exposure is influenced by the dust particle size [87, 88, 89]. Fine particles such as particulate matter (PM) of size 2.5 μm ($PM_{2.5}$) in the atmosphere of e-waste recycling areas serve as carriers for some organic compounds, posing potential adverse health effects [90]. Dust particles of sizes below 2.5 μm ($PM_{2.5}$) and 10 μm (PM_{10}) can be inhaled into the respiratory system [91, 92] but particle sizes below 250 μm [93] adhere to the skin and can be ingested. High levels of PAH and Phthalate were found in $PM_{2.5}$ generated by e-waste recycling [94]. PAHs in the atmosphere exist in the vapour phase or sorbed onto particulate matter (solid phase) [95, 96, 97]. Depending on the source of the PAH, there could be multiple exposure routes [98]. Kuo et al. [99] found a significant correlation between PAH concentration and quantity of dust in the air. Adsorption of PAHs onto the particulate phase is affected by humidity [100] and nature of suspended particulates [97]. Combustion of chlorinated and brominated organic compounds leads to the dispersion of fine ashes containing PCDD/Fs and PBDEs. Dust containing PAH, PCDD/Fs and PBDEs are transported to areas even outside the recycling sites and the extent is partly dependent on the wind speed and direction.

Dermal uptake from airborne organic contaminants by e-waste workers is as significant, if not higher than inhalation [101]. Human exposure to organic contaminants through the skin occurs through inadvertent touch with contaminated dust or soil [60, 102], air-to-skin transport [103, 104] and fabric-mediated transport [105, 106, 107, 108] of both particulate and gaseous contaminants. Children and other immediate family members of e-waste recycling workers are exposed to toxins in the clothes and body of workers. Absorption of organic compounds by the skin is inversely proportional to the molecular weight and partition coefficient, K_{ow} and directly proportional to the water solubility [109, 110] and length of exposure [101]. Other potential exposure through this pathway is by the direct deposition of contaminants on plants, grazing domestic and wild animals.

Toxicity levels of E-waste-related organic compounds in Ghana

Air

Two papers reported the toxicity levels of PCBs and PCDD/Fs in the ambient air at e-waste recycling sites in Ghana. Amoyaw-Osei et al. [6] estimated the amount of dioxin emissions from cable burning in the Greater Accra region while Hogarh et al. [111] monitored atmospheric PCBs in several locations in Ghana including Agbogbloshie. The preliminary estimate of PCDD/F emissions to air amounted to approximately 3 g/year. This value is equivalent to up to 15% of dioxin emissions from different sources in the EU for 2005 [112]. Again, PCB concentration at Agbogbloshie was 4.64 ng/m^3. About 11.1 ng/m^3 PCB concentration was measured in plumes from e-waste opening burning at Agbogbloshie. Public risk (adults residing near the Agbogbloshie e-waste site) to DL-PCB through inhalation was 4.2 pg/TEQ/day. However, direct e-waste workers are exposed to 3.86 pg/TEQ/day. The concentrations of PCBs and PCDD/Fs measured in the ambient air at Agbogbloshie were within values of PCBs (4.23–11.35 ng/m^3; 0.050–0.859 pgTEQ/m^3) and PCDD/Fs (2.91–50.6 pg/m^3) reported in the ambient air of an e-waste site at Taizhou, China [113]. At Agbogbloshie, the wind blows from the south or southwest towards the nearby residences in northern areas [114]. The implications of the values observed and the wind direction are that the nearby residents are at higher risk of exposure to DL-PCB through inhalation than direct e-waste workers. But e-waste workers residing in Agbogbloshie could be at elevated risk (about 6.65 pg/TEQ/day) due to cumulative effects. There are no studies reporting on PBDEs in the ambient air at Agbogbloshie as has been reported in China [115, 113, 116] and Thailand [117]. The limited studies on organic compounds in the air at Agbogbloshie and other e-waste sites in Ghana represent a major research gap.

Human body fluids

Three organic compounds (PCBs, PAH and PCDD/Fs) have been assessed in the blood, urine and breast milk of humans working or residing at or near the Agbogbloshie e-waste site. Table 2 shows a summary of the findings of studies on organic contaminants in human body fluids at Agbogbloshie. Test participants selected for studies on health status are direct e-waste workers, secondary e-waste workers (food, water and beverage sellers) and a control population (people who have neither visited nor resided at or near e-waste sites) [18, 118, 23, 20,

Table 2. Studies related to organic contaminants in human bodily fluids at Agbogbloshie e-waste recycling site.

Organic Contaminant	Media	Sample Location	Sampling Period	Median Conc.	TEQ (pg/g)	Daily Intake (µg/kg bw)	Sample Size	Reference
PCB	Blood	E-waste workers	October 2011	0.082 µg/g	–	–	21 males	Wittsiepe et al. [36]
PCB	Breast milk	Nursing mothers	2014–2016	3.64 ng/g lipid wt	–	0.02	105	Asamoah et al. [18]
PCDD/F	Blood	E-waste workers	October 2011	–	12.1	–	39 males	Wittsiepe et al. [36]
PAH	Urine	E-waste workers	October 2011	3.94 µg/g creatinine	–	–	72	Feldt et al. [20]

12]. The control populations were mostly selected from the neighbourhoods of Kwabenya North and Makola, both in Accra but far away from Agbogbloshie and without e-waste activities.

Asamoah et al. [18] determined PCBs in the breast milk of primiparae (47 participants) and multiparae (58 participants) mothers residing or working in and around the Agbogbloshie e-waste site and a reference site (24 km from Agbogbloshie; with no known e-waste activities). The total PCB concentration in the breast milk of mothers at Agbogbloshie was 3.64 ng/g lipid wt compared with 0.026 ng/g lipid wt at the reference site. The PCB congeners with the highest concentrations in the breast milk were PCB-18, PCB-28 and PCB-138 which accounted for about 75% of the sum of mean concentrations of PCBs. In another study, three different congeners of PCBs (153, 138, and 180) were measured in the blood of 39 e-waste workers at Agbogbloshie which were significantly higher (arithmetic mean of 0.021–0.036 µg/l whole blood) than the concentrations measured in the controls [36]. The authors reported that they found no correlation between exposure to PCB and e-waste activities at Agbogbloshie, but the relatively higher concentration recorded in the exposed population compared with the controls is suggestive of e-waste recycling being a possible contributor to PCB in human body fluids. PCBs have also been reported in human milk in Accra. Asante et al. [119] found an increased internal exposure to PCBs (62 ng/g lipid wt) through human milk in Accra between 2004 and 2009.

Dietary intake is a major source of exposure to PCBs. Asamoah et al. [18] and Wittsiepe et al. [36] did not assess the contribution of other sources of PCBs (such as the diet of the mothers) to the total PCB in the breast milk of nursing mothers at Agbogbloshie which may have contributed to the concentration reported. In the study conducted in Accra by Asante et al. [119], ten (10) different PCB congeners (PCB-28, 74, 99, 118, 138, 153, 170, 180, 183 and 187) were measured as against seven (PCB-18, 28, 52, 101, 138, 153 and 180) by Asamoah et al. [18] and three (PCB-138, 153 and 180) by Wittsiepe et al. [36] both at Agbogbloshie. The differences in the number and types of congeners measured probably contributed to the differences in the values recorded. The predominant PCB congeners recorded at Agbogbloshie [18] were PCB-28, 18 and 138 but those recorded in Accra [119] and Agbogbloshie [36] were PCB 153, 138 and 180. Even though the concentration of PCB-153, 138 and 180 were different in absolute terms (with Accra recording higher values), the trend was the same.

PCBs in the breast milk of mothers are passed on to the babies. Similar trends of PCB concentrations have been reported in India [15], Vietnam [19] and China [10, 13]. An increased daily intake of PCBs by infants have been associated with a lower IQ, increased behavioural problems and childhood asthma [120]. The daily intake of PCBs by infants through the breast milk in Ghana was calculated using an average baby weight of 5 kg and average milk consumption of 700 g/day. The daily intake of PCBs from the breast milk of nursing mothers at Agbogbloshie was 0.02 µg/kg bw/day [18]. This value is about 20 times lower than the daily intake of PCBs (0.4 µg/kg bw/day) through human milk reported by Asante et al. [119] in Accra in 2009.

The high intake of PCBs in Accra suggests that people are exposed to PCBs from sources other than e-waste burning such as consumption of contaminated fish and biomass burning. PCBs have been measured (mean concentration of 62 ng/g lw) in fishes obtained from 6 water bodies in Ghana [121]. The predominant congeners were PCB-153, -138 and -180 just like those found in the breastmilk of nursing mothers in Accra [119] and Agbogbloshie [36]. Commercial and homemade baby foods have been found to also contribute to babies' exposure to PCBs [122, 123]. Exposure to PCBs by babies in Agbogbloshie was from their mothers' breastmilk only since the mothers who participated in the study were practising exclusive breastfeeding. Using the FAO and

WHO allowable daily intake of 6 µg/kg [124], babies are at no risk. The daily PCB intake of 0.02 µg/kg bw/day recorded by Asamoah et al. [18] was much lower than the FAO/WHO guideline value. However, some mothers recorded up to the minimal risk value of 0.03 µg/kg bw/day [75], indicating potential health risk to their babies.

PAHs and PCDD/Fs which are end products of incomplete combustion of e-waste components have been measured in the blood and urine of e-waste workers. High concentrations of 6 PAH metabolites (1-, 2-, 3-, 4- and 9-OH-phenanthrenes and 1-OH-pyrene) were measured in the urine of e-waste workers at Agbogbloshie. The highest median concentration of 1.27 µg/g creatinine was measured for 1-OH-pyrene with the least concentration of 0.21 µg/g creatinine being measured for 4-OH-phenanthrene [20]. Similarly, an increase in internal PCDD/F exposure of about 5 pg/g lipid base WHO_{2005}-TEQ per year was recorded at Agbogbloshie [36]. However, the study failed to establish a causal relationship between exposure to PAH metabolites or PCDD/F and e-waste recycling. Other potential sources of PAHs common in Ghana are smoke from burning of biomass fuel, vehicle exhaust fumes, combustion of domestic waste and tobacco smoking. Considering non-smoking individuals, a molar sum of 6 PAH metabolites (1-, 2-, 3-, 4- and 9-OH-phenanthrenes and 1-OH-pyrene) was 1.29 µmol/mol creatinine [20]. It can be inferred that smoking is not a contributor to PAH in the test participants. The urinary PAH metabolites measured at Agbogbloshie were significantly higher in the exposed compared to the control participants, indicating a contribution of e-waste activities to the PAH levels in the exposed population. Moreover, the exposed population complained more frequently of cough, chest pain and dizziness. Long-term exposure to PAHs affects the immune system and causes cataracts, kidney and liver damages, as well as breathing problems [125].

The high levels of organic compounds found in the soil/dust and air at Agbogbloshie may have contributed to the increased exposure of humans. The location of Agbogbloshie relative to food sources (such cattle/goat pasture and domestic fowls) increases people exposure to organic compounds. Chlorinated dioxins (220-folds), PCBs (4-folds) and DL-PCBs (171-folds) concentrations higher than European Food Safety Authority tolerable daily intake have been reported in eggs of free-range domestic fowls at Agbogbloshie [126].

Soil and ash

Many studies have assessed the concentration of organic pollutants, particularly in the soils and bottom ash from open burning areas at the Agbogbloshie e-waste recycling site. Table 3 summarizes the results of these studies. Generally, all the soil samples taken from e-waste sites in Agbogbloshie by researchers for analysis have been sampled from a depth not exceeding 5 cm. To the best of our knowledge and from the literature reviewed, data on contamination status of soil below the sampled depth of 5 cm is virtually non-existent.

High levels of PAHs have been observed in the topsoil at Agbogbloshie. Even at non-open burning areas in Agbogbloshie (such as the dismantling site, at a mosque, a personal computer repairers' shop and a police post), the concentration of $\sum_{18}$ PAHs was between 3,066 and 5,555 ng/g. At open burning sites, the concentration of $\sum_{15} PAH$ in the soils ranged from 390–710 ng/g [127] implying that the soil is weakly contaminated according to soil contamination classification by Maliszewska-Kordy-bach [128]. The

Table 3. Studies related to organic contaminants in soils from burning areas at Agbogbloshie e-waste recycling site.

Organic Contaminant	Sampling Period	Median Conc. (ng/g)	TEQ (pg/g)	Sample Size	Reference
PAH	March–April 2015	4822	–	3	Daso et al. [30]
Cl/Br-PAH	August 2010	36–110*	0.045	5	Tue et al. [130]
Cl -PAH	August 2013	21–29*	0.017	2	Nishimura et al. [127]
Br-PAH	August 2013	5.8–12*	0.0009	2	Nishimura et al. [127]
PAH	August 2013	390–710*	1.6	2	Nishimura et al. [127]
PCDD/F	2008–2010	12.4–280	31–121	8	Brigden et al. [28] Fujimori et al. [132] Tue et al. [131]
DL-PCB	August 2010	5.5	11–42	7	Fujimori et al. [132] Tue et al. [131]
PBDD/F	August 2010	8.6–930	262	7	Fujimori et al. [132] Tue et al. [131]
PBDE	First Quarter 2015	54.8*	–	18	Akortia et al. [68]

*Mean concentration.

concentration of $\sum_{15} PAH$ was 13–25 times higher than the control (30 ng/g) but about eight times lower than the results obtained by Daso et al. [30]. In their study, Daso et al. [30] reported the sum of 18 PAHs as against 15 PAHs reported by Nishimura et al. [127] and this could have contributed to the significantly lower values obtained. It could also be that the samples were collected from separate locations relative to the actual e-waste burning sites at Agbogbloshie. Using low-to-high molecular weight PAH ratio, pyrogenic activities were found to be the source of PAHs at Agbogbloshie. The carcinogenic risk to PAHs evaluated using benzo[a]pyrene toxicity equivalence factors (TEFs) ranged from 111 ng/g to 454 ng/g. When compared with the Canadian soil quality guidelines [129], none of the sampling sites had TEFs exceeding the safe value (600 ng/g), thus indicating minimal cancer risk from PAHs. However, the TEFs obtained by Daso et al. [30] show that prolonged exposure to pollutants may increase their potential cancer risk over time. Both Br- and Cl-PAHs were identified only in open burning areas. Three- to five-ring Cl-PAHs (mean of 190 ng/g dw) and Br-PAHs (mean 36 ng/g dw) were the most detected in topsoils from the e-waste burning areas [130]. The presence of three-ring Cl/Br-PAHs and absence of Cl/Br-PAHs in non-burning areas of Agbogbloshie and non-e-waste areas showed that the contaminations were originated from open burning of e-waste. The maximum toxic equivalency (TEQ) concentration of Cl/Br-PAHs in the soil from open e-waste burning areas was reported as 0.045 pg/g dw by Tue et al. [130] but significantly lower values (0.00089–0.017 pg TEQ/g) were obtained by Nishimura et al. [127]. PAHs in either the gaseous or solid (sorbed onto PM) phase are carried to locations outside the e-waste sites.

Surface soil samples from open burning areas at Agbogbloshie e-waste site contain high concentrations of PBDD/F, PCDD/F and DL-PCBs compared with non-open burning sites. Total concentrations of PBDD/Fs (median 930 ng/g), PCDD/Fs (median 280 ng/g) and DL-PCBs (median 42 ng/g) were found in the open burning areas of Agbogbloshie. The concentrations of PBDD/Fs, PCDD/Fs and DL-PCBs obtained by Tue et al. [131] were within the values obtained by Fujimori et al. [132]. Soil samples from burning areas also contain chlorinated, brominated and mixed halogenated PBDD/Fs, PCDD/Fs, PXDD/Fs. At all sampling sites, total concentrations of PBDD/F, PCDD/F and DL-PCBs were higher by one to two orders than in the non-open burning areas and approximately 100 times higher than in non-e-waste locations of Accra. PBDFs were the most dominant in samples from open burning areas, indicating that burning of plastics is the source of contamination. WHO-TEQ for PCDD/Fs and DL-PCBs in the open burning areas were in the ranges of 3500–7300 pg/g and increased by 1.5–3.5 folds when PBDD/Fs were included [131]. However, Fujimori et al. [132] found significantly lower TEQ concentrations (11 pg-TEQ/g) of DL-PCBs which was still higher than the Canadian soil guideline value of 4 pg TEQ/g [60]. These results are higher than the action level of 1000-pg/g adopted by various countries. Brigden et al. [28] reported 31 pg TEQ/g of PCDD/F levels in ash-contaminated soil at the Agbogbloshie market. They also identified PAHs, chlorinated benzenes, PBDEs, phthalate esters and triphenyl phosphate (TPP), in the samples of top soil from an e-waste recycling site in Koforidua, [28] but they reported the numbers of compounds reliably identified in the samples and not the concentrations. People are exposed to organic compounds through dermal uptake. Dust particles contaminated with PAHs, PCBs, and PCDD/Fs are transported to areas even outside the recycling sites thereby increasing their spatial extent.

Aside PCBs, PCDD/Fs and PAHs, PBDE concentration (mean of 54.8 ng g−1 dw) comprising of eight (8) BDE congeners (BDE -28, -47, -99, -100, -153, -154, -183, -209) were identified in the surface soils at different locations in Agbogbloshie [68]. Adult and children exposure to BDEs (−47, −99, −153) through soil ingestion have slightly exceeded their corresponding Reference Dose (RfD). However, a lower value was recorded for BDE-209, indicating the likelihood of minimal health risk. The BDE-47 and BDE-99 hazard quotient (HQ) for children were respectively 0.91 and 0.95 at the 95th percentile. This indicates the need to pay attention to the non-carcinogenic health risk for local children. Apart from exposure to organic compounds through inhalation, children playing in the vicinity of Agbogbloshie are at high risk of exposure through ingestion and dermal contact [73]. Domestic animals foraging at Agbogbloshie site may be exposed to organic compounds and subsequently transfer the contaminants to humans through the food chain. More recently, Petrlik et al. [126] found high levels of DL-PCBs DL-PCBs

(195 pg TEQ/g fat), PCDD/F (661 pg TEQ/g fat) and PBDD/Fs (300 pg TEQ/g fat) in the eggs of free-range chickens that forage at the Agbogbloshie e-waste site. But, the hazard index (HI) for BDE (-47, -99, -153, -209) congeners were below 1.0, indicating an overall low health risk. Higher concentration of organic compounds (PCBs, PCDD/Fs, PAHs and PBDEs) in the surface soils at Agbogbloshie could be washed by surface runoff into surface water bodies. As has already been mentioned, the low solubility of PAHs, PCDD/Fs, PCBs and PBDEs [74, 80, 78, 79] limits human exposure through drinking of contaminated water but highly through the aquatic food chain.

Sediments

The only study our search found reporting the toxicity levels in sediments was conducted by Brigden et al. [28]. In their study, they collected samples from a shallow lagoon located near the Agbogbloshie market where e-waste is openly burnt. The concentration of PCDD/F reported in the sediments was 988 pg TEQ/g. The congener profile of the PCDD/F was consistent with combustion residues from PVC coated wires and other e-waste recycling sites [133, 134, 34]. The higher PCDD/F levels in the lagoon sediments could be attributed to the direct deposition of ashes formed during open burning and washing of contaminated soils into the lagoon from open burning sites and surrounding soils by surface runoff. The PCDD/F concentration in the sediment is quite similar to the threshold defined for seriously contamination soils and sediments in the Netherlands (1,000 pg/g TEQ) [135], and the soil clean-up level in the United States [136]. Whiles the concentration is considered lower, PCDD/Fs can bioaccumulate and biomagnify in aquatic organisms over long periods of exposure, posing threat to the health of humans that consume those organisms. Considering the potential wider spread, large number of people who could be affected and the location of e-waste sites relative to important water bodies (particularly at Agbogbloshie), the presence of organic compounds from e-waste sources in the aquatic medium requires extensive research.

Conclusions

E-waste recycling in most developing countries such as Ghana is performed mainly through the informal sector, which accounts for up to 95% of the recycling activities. Their recycling practices, being more rudimentary, and involving crude methods like open burning of e-waste components or acid leaching without protective equipment, put the health of both the primary and secondary workers as well as the nearby residents at risk. The predominant organic contaminants associated with e-waste recycling in Ghana are PCDD/Fs, PBDEs, PAHs, DL-PAHs and PCBs. People are potentially exposed to multiple e-waste contaminants through inhalation, ingestion of contaminated soils and dermal contact. Generally, there are high concentrations of PCDD/Fs, PBDEs, PAHs, dioxin-like PAHs and PCBs in soils at Agbogbloshie compared with international guideline values.

Even though relatively high concentrations of PCBs, PCDD/Fs and PAHs have been measured in human body fluids (blood, urine and breastmilk), no causal relations have been found between organic compounds in human bodily fluids and e-waste burning. But the high concentrations in the exposed population compared with the controls suggest that e-waste burning is a potential contributor to human exposure to organic compounds at Agbogbloshie. The presence of several schools, human settlements and informal children playing grounds surrounding the Agbogbloshie e-waste sites poses a greater risk to children. Moreover, the location of the e-waste site relative to a goat/cattle pasture and easy access by domestic animals present additional pathways for transporting the e-waste-related organic compounds through the food chain. The wind direction at Agbogbloshie suggests that toxic organic compounds from open burning of e-waste are transported through the air to non-e-waste sites exposing many innocent people to organic contaminants. The current Hazardous and Electronic Waste Control and Management Act (Act 917) and other management regulations (such as LI 2250) prevent the open burning of e-waste components. The strict implementation of the regulations is likely to eliminate the open burning and reduce public exposure to harmful organic compounds and heavy metals. But the presence of organic compounds in soils have long-term implications on the health of people living or working at e-waste sites years after the dangerous informal recycling practices are stopped. Government intervention is required to remediate the contaminated sites. Information on the types and concentrations of organic compounds and other contaminants in the deeper parts of the soils is necessary for decision-making on the best and cost-effective remediation method to select for the sites.

Most of the studies we reviewed focused on soils and ashes as compared to human body burdens. In particular, data on the organic contaminant levels in the air and food at the Agbogbloshie recycling site are limited. Further studies are, therefore, required to identify and document levels of organic contaminants from e-waste sites in other environmental media (air, water and foodstuffs) and body burdens of children living and illegally working at the e-waste sites as well as in secondary e-waste workers. Further research is required to verify the changes in contaminant concentrations in different environmental media at Agbogbloshie following the passage of the e-waste regulation in 2016.

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