E-Waste Disposal Effects on the Aquatic Environment: Accra, Ghana

Jingyu Huang, Philip Nti Nkrumah, Desmond Ofosu Anim, and Ebenezer Mensah

Contents

J. Huang
Ministry of Education Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Hohai University, Nanjing, China

P.N. Nkrumah (✉)
Ministry of Education Key Laboratory of Integrated Regulation and Resource Development on Shallow Lakes, Hohai University, Nanjing, China

Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology, PMB, Kumasi, Ghana

College of Environment, Hohai University, No. 1 Xikang Road, Nanjing 210098, China

D.O. Anim
College of Environment, Hohai University, No. 1 Xikang Road, Nanjing 210098, China

E. Mensah
Department of Agricultural Engineering, Kwame Nkrumah University of Science and Technology, PMB, Kumasi, Ghana

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1 Introduction

In most developing countries, the rapid pace of urbanization is a challenge to urban environmental management. One major challenge of waste management facing some urban areas is electronic waste (e-waste). The increasingly rapid evolution of electronic technology, coupled with rapid product obsolescence, has compounded the e-waste problem (Otsuka et al. 2012).

The amount of e-waste generated globally is growing at a rate nearly three times faster than the growth of overall municipal solid waste (Schluep et al. 2009). According to UNEP (2010), the annual e-waste generated worldwide is estimated to be 20–50 million tons (t). Unfortunately, between 50% and 80% of such e-waste is prospectively exported to developing countries like Ghana, China, India and Nigeria (Puckett and Smith 2002; UNEP 2005; Orisakwe and Frazzoli 2010; Environmental Investigation Agency 2011; Lundstedt 2011).

The University of Ghana's Institute for Environment and Sanitation Studies reported that Ghana has been identified as a popular dumping ground for old electronics (Koranteng and Darko 2011), making e-waste an alarming and growing menace in the country. This accumulated e-waste is poorly managed in the country, because proper systems for recycling and disposal of them are lacking (Nordbrand 2009; Darko 2010). According to Amoyaw-Osei et al. (2011), hundreds of tons of e-waste end up at the scrap yards in Ghana every month, where it is disassembled to extract valuable components and metals. Specifically, the main center for recovering and recycling e-waste materials is the Agbogbloshie Scrap Market in the Greater Accra region (Brigden et al. 2008). Prakash et al. (2010) estimated that about 8,000 metric t of e-waste is being treated annually at the Agbogbloshie metal scrap yard.

The uncontrolled dumping and inappropriate recycling of e-waste poses serious threats to human health and the environment at large (Prakash et al. 2010), because e-waste contains a multitude of hazardous substances that may be released as the waste is handled and processed (Lundstedt 2011; Tysdenova and Bengtsson 2011). The toxic chemicals that exist in e-waste include a wide range of heavy metals, such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As) and nickel (Ni), and also persistent organic compounds, such as brominated flame retardants (BFRs) and phthalates. Other chemicals that appear in e-waste include the polychlorinated biphenyls (PCBs), nonylphenol (NP), and triphenyl phosphate (TPPs), among others (Azuka 2009; Robinson 2009). A study conducted by Greenpeace International (2008) at the Agbogbloshie scrap yard showed that some samples contained Cd, Hg and Pb in quantities that are considered especially toxic to aquatic life.

Unfortunately, according to the Director of the Chemicals Control and Management Centre of the Ghana Environmental Protection Agency, data on the adverse impact of e-waste on human health and the environment in Ghana is highly limited (Pwamang 2009). It is sad to note that research conducted to date at the main Ghanaian e-waste dumpsite (Agbogbloshie) has been only on a small scale, and as a result, the true extent of e-waste chemical contamination at the site is largely unknown (Caravanos et al. 2011). Moreover, to the best of our knowledge, the environmental concerns of e-waste in particular have not yet been properly addressed in Ghana (Agyei-Mensah and Oteng-Ababio 2012; Asante et al. 2012; Otsuka et al. 2012; Caravanos et al. 2013; Riederer et al. 2013).

Notwithstanding the dearth of knowledge, there is concern for the contamination at the Agbogbloshie disposal site because of its close proximity to other water bodies, such as the Odaw River and its estuary, and the Korle lagoon. This near proximity, coupled with the incessant floods that occur in the area, enhances the probability that aquatic life will be exposed to e-waste. According to Nixon et al. (2007), Korle Lagoon, which is in the downstream estuary, has become one of the most polluted water bodies on earth, and this is clearly a very serious concern.

In the present paper, our goal is to review the potential hazards posed by e-waste contaminants on the aquatic environment at the Agbogbloshie disposal site in Ghana, which we contend typifies the situation in the majority of developing countries. To achieve our goal, we estimated the volume of e-waste disposed of in Ghana, and evaluated the available e-waste management options. We sought to know what chemical contaminants are commonly detected in the various kinds of e-waste disposed of in Ghana and assessed the significance of the Agbogbloshie disposal site's proximity to nearby water bodies. In addition, we analyzed the factors that may facilitate the contamination of the water bodies by hazardous substances that exist in e-waste. Ultimately, we assessed the possible adverse effects to aquatic life from release of e-waste-associated chemical contaminants (primarily heavy metals and organic compounds).

2 Management of E-Waste in Ghana

As mentioned in the introduction, Ghana has become a popular dumping ground for e-waste. Despite the enormous amounts of e-waste that is dumped in Ghana, there is no clear measure for how many used-computer or other electronic-equipment shops exist around the country; nor is the quantity of e-waste that now exists in the country well established. Orisakwe and Frazzoli (2010) reported that the main reason for this is that records are simply not kept on these parameters. However, limited data do suggest a rise in the quantity of e-waste that has been imported to Ghana since 2003 (Fig. 1). The main components of e-waste processed at Ghanaian scrap yards include obsolete computers and televisions (Brigden et al. 2008).

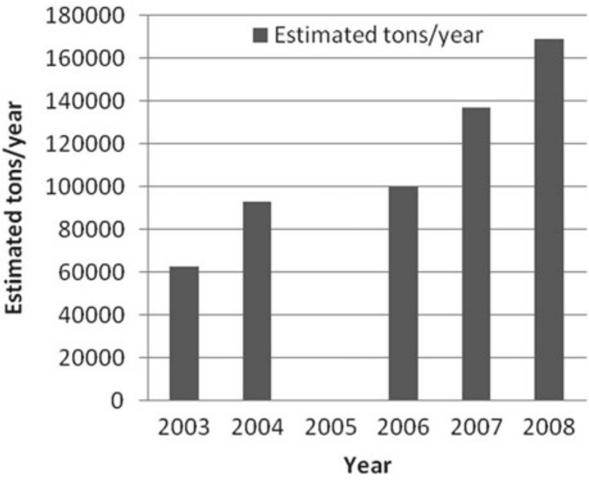

Fig. 1 Estimated quantity of E-waste imported into Ghana (Adapted from UN Comtrade 2010)

2.1 E-Waste Recycling in Ghana

The e-waste recycling activities in Ghana are mainly performed by the informal sector. This sector uses rudimentary methods to salvage copper and other metallic components that can be sold. For example, the e-waste is dismantled and sometimes burned (Amoyaw-Osei et al. 2011; Lundstedt 2011). During the recycling process, simple hand tools such as hammers, chisels, or even stones are employed to break electronic devices down to their individual components. Materials of no value are disposed of in a large area at the disposal sites. Such materials are piled up on the dump site and are periodically burned to reduce volume. It must be noted that wet chemical leaching processes, often associated with the recovery of precious metals from printed wiring boards (PWBs), have not been observed in Ghana (Prakash et al. 2010; Amoyaw-Osei et al. 2011). However, there are indications that these PWBs are exported to Asia for further processing (Grant and Oteng-Ababio 2012).

2.2 Proximity of the Agbogbloshie E-Waste Disposal Site to Water Bodies

Agbogbloshie is located geographically at 05°35′N and 00°06′W (Fig. 2). The town covers an area of approximately 16 km^2 and has a population of about 40,000. It lies within the tropics.

The Agbogbloshie scrap yard, as depicted in Fig. 2, is situated on flat ground on the left bank of the Odaw River, and in the upper reaches of the Korle Lagoon in Accra (Amoyaw-Osei et al. 2011; Caravanos et al. 2011; Oteng-Ababio 2012). These water bodies adjacent to the disposal site form part of one of the major catchments (Odaw-Korle) in the Accra metropolis, and cover an area of 250 km^2.

The mean annual rainfall in Ghana is estimated to be 1,187 mm (FAO 2005) and the average annual rainfall in the Accra Metropolitan Assembly is about 730 mm (Accra Metropolitan Assembly 2006). This region has a distinct rainy season, in which routine heavy rains fall primarily during two rainy seasons. There are two rainfall peaks, one notably in June and the other in October. Rain usually falls during intensive short storms and gives rise to local flooding. The flooding particularly affects low-lying areas such as the Agbogbloshie scrap yard. We must emphasize that the lower-lying lagoons and the Odaw river, which ultimately flow into the ocean, are just adjacent to the disposal site. Therefore, the threat that moving water will leach or wash contaminants into the local water bodies is high; once such contaminated run-off occurs, the threat to aquatic organisms in these water bodies is also high. Actually, Biney (1998) classified urban run-off as one of the main types of pollution that reaches the Odaw-Korle catchment. Brigden et al. (2008) confirmed that many chemicals present in the Korle lagoon sediment were the same as, or were similar to, those found at the contaminated sites where waste was burned or processed; site sampling suggested that pollutants migrated from the burning sites

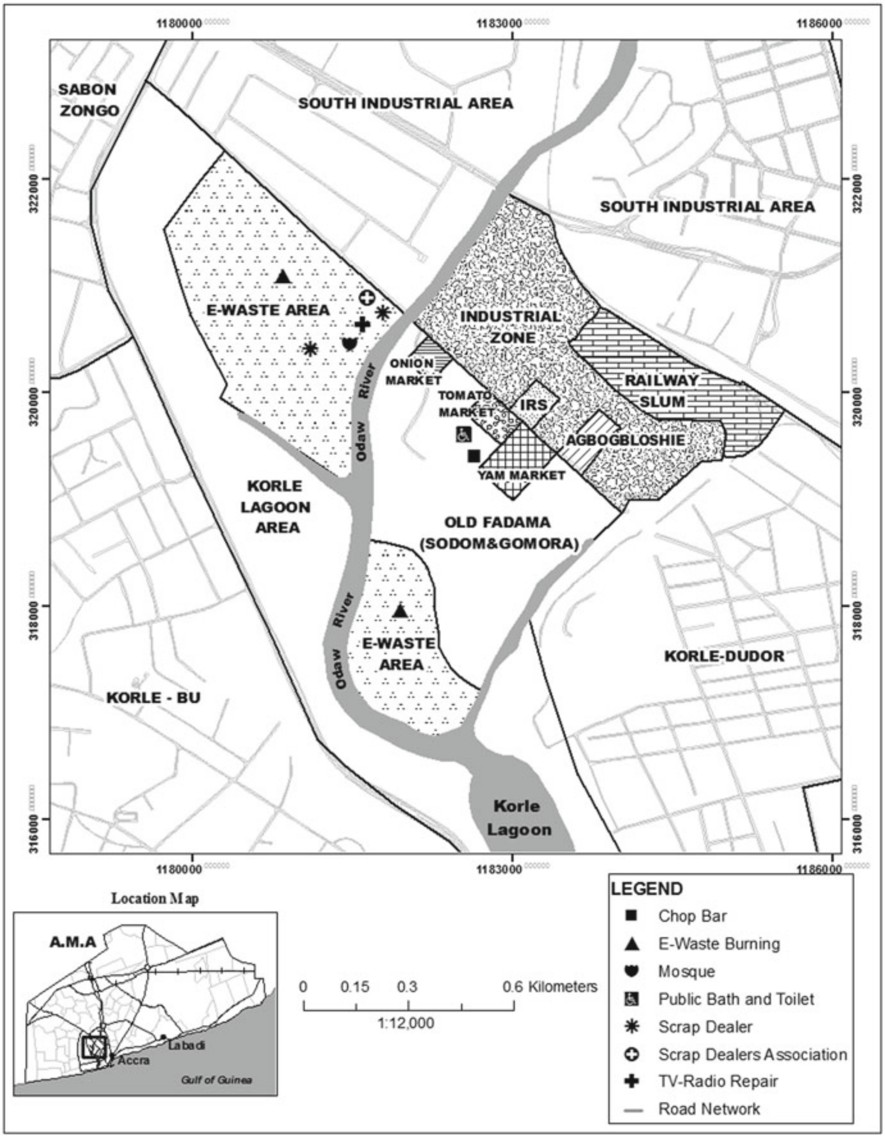

Fig. 2 Map of the Agbogbloshie E-waste recycling site in Ghana (Adapted from Oteng-Ababio 2012)

to surface waters, probably as a result of heavy rainfall and flooding. The direct disposal of e-waste into water bodies is augmented by the introduction of these same contaminants into the same water bodies via leaching.

Another mechanism that is likely to introduce e-waste contaminants to the local water bodies is atmospheric deposition. The region lies within the dry coastal equatorial climatic zone and is therefore rather dry (Ghana Districts 2006). This fact, coupled with the open burning practices that take place during e-waste recycling, results in the formation of thick fumes. The fume particles may be introduced to the nearby surface waters through wet or dry atmospheric deposition. We describe the contaminants that are introduced to the local water bodies in Sect. 3.

3 E-Waste Contaminants

E-waste contains numerous hazardous chemicals and materials (e.g., heavy metals such as lead and cadmium, and many chlorinated or brominated organic compounds). Some of the types of chemicals found in e-waste are identified in Table 1.

The occurrence of these contaminants within the local environment of the e-waste recycling site in Ghana cannot be disputed. Brigden et al. (2008), Caravanos et al. (2011) and Otsuka et al. (2012) have tested soil and ash samples at the Agbogbloshie site, and have identified high concentrations of toxic metals (in quantities that were as much as 20-times above background levels), such as zinc, lead and copper, and organic chemicals, such as the phthalates and

Table 1 The nature of chemical contaminants that exist in E-waste

Chemical	Source of these components
Lead	Glass of cathode ray tubes (CRT) in televisions and monitors, lead-acid batteries, polyvinyl chloride (PVC) cables
Arsenic	Integrated circuit boards
Beryllium	Connectors; Mother boards and finger clips
Polychlorinated biphenyls (PCBs)	Electrical transformers, capacitors, PVC
Cadmium	Switches, solder joints, Housing, PVC cables, cathode ray tubes, rechargeable Batteries
Polybrominated diphenyl ethers (PBDEs)	Casings
Polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs)	Formation during thermal processes
Nonylphenol (NP)	Insulators, Housing, Casing
Triphenyl phosphate (TPP)	Casings of computer monitors
polychlorinated naphthalenes (PCNs)	Capacitors, insulated wires
Mercury (Hg)	Batteries, flat screen electronic displays, switches, relays, Housing
Phthalates (e.g., di(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP))	PVC
Polycyclic aromatic hydrocarbons (PAHs)	Formation during thermal processes
Chromium	Steel housing
Barium	CRT, Vacuum tubes

Source: Adapted from Nordic Council of Ministers (1995), Matthews (1996), Microelectronics and Computer Technology Corporation (1996), OECD (2003), Brigden et al. (2005), Azuka (2009), Environmental Investigation Agency (2011) and Lundstedt (2011) polybrominated diphenyl ethers (PBDEs). However, we also note that studies on the detection of harmful chemicals in the sediments of the nearby water bodies are extremely limited.

4 Effects of E-Waste Contaminants on Aquatic Organisms

Obviously, the introduction of the e-waste contaminants to the local water bodies poses hazards to the local aquatic organisms. A study conducted by the Institute for Applied Ecology (the Öko-Institut) indicated that local residents living near the lagoon, where uncontrolled dumping and e-waste recycling activities occur, lamented the adverse impacts of the site on the aquatic life of nearby water bodies (Prakash et al. 2010). This study revealed that the lagoon, which used to be a common fishing ground for the residents of the local communities until a few years ago, is now heavily polluted. As a result, many aquatic species in the lagoon have been eliminated. Amoyaw-Osei et al. (2011) also observed that the Odaw River, which was formerly an important fishing ground, has become dead because of the extensive pollution caused by uncontrolled dumping and the crude processing of e-waste in the area.

According to the US EPA (1998), an ecological risk assessment method can be applied to predict the potential adverse effects of bioaccumulative pollutants to organisms by comparing the exposure concentrations to an effect concentration. In Table 2, we compare sediment concentrations of contaminants from Korle Lagoon with sediment toxicity thresholds for saltwater benthos proposed by Australia, Canada, and by Long et al. (1995) working in the United States. The metals posing the highest potential risk in Korle Lagoon sediments appear to be copper, lead and zinc, whose concentrations ranged from 20-times higher than the sediment

Table 2 A comparison of high-level contaminants in Korle Lagoon, with sediment quality guideline values for saltwater benthos of Australia and New Zealand (ANZECC) and Canada. In columns 2–4, two values are given for each sediment quality guideline; the lower one is the one below which no effects are expected; the higher one is associated with an increased probability of adverse effects (concentrations are given in mg kg^{-1} dry wt)

Contaminant	Korle Lagoon[a]	Long et al. (1995)	ANZECC 2012[b]	Canada 2012[c]
Cadmium	6	1.2/9.6	1.5/10	0.7/4.2
Chromium	34	81/370	80/370	52.3/160
Copper	2,260	34/270	65/270	18.7/108
Lead	1,685	47/218	50/220	30.2/112
Mercury	<0.5	1.0/3.7	0.15/1	0.13/0.7
Zinc	2,425	150/410	200/410	124/271

[a] Source: Brigden et al. (2008)
[b] ANZECC (2012)
[c] CCME (2012)

concentration most associated with adverse effects to benthos (Cu), 15-times higher (Pb), and 5.6-times higher (Zn).

The sediment toxicity thresholds shown in Table 2 do not account for site-specific influences on the bioavailability of contaminants, and pertain mainly to toxicity arising from short-term (10–30 day) sediment exposures, rather than chronic toxicity, and effects arising from the concentration of contaminants in the aquatic food chains. Thus, Table 2 incompletely characterizes potential risks associated with Korle Lagoon sediments and surface waters. Nevertheless, concentrations of copper, lead and zinc are high enough in the sediments to warrant further investigations into the effects of these and other contaminants, and implementation of controls on their release into the water bodies. It must be pointed out that we have predicted pollutant effects on aquatic life, based on their release from sediments into the water column, which is expected from both diffusion and advection, and depends on the pH and Eh of the sediments (Reuber et al. 1987; Simpson et al. 1998, 2000, 2002).

4.1 Effects of Heavy Metals on Aquatic Life

The adverse impacts that heavy metals impose on aquatic life have been well established. Heavy metals are highly persistent, toxic in trace amounts, and can potentially induce severe oxidative stress in aquatic organisms (Frazier 1979; Nammalwar 1983; Forster and Whittmann 1983; Meria 1991; Al-Masri et al. 2002; Karbassi et al. 2006; Guo et al. 2009; Woo et al. 2009; Jakimska et al. 2011). Aquatic organisms may absorb heavy-metal pollutants directly from water or indirectly via uptake from the food chain.

Metals may typically act together to potentiate toxicity (Corrill and Huff 1976). Nammalwar (1983) addressed both the indirect and direct effects by which heavy metals affect aquatic organisms. The author noted that indirect effects are produced on food chain organisms and via ecological stress, whereas direct effects are observed on behavior, migration, physiology, metabolism, reproduction, development and growth of aquatic animals. In this review, we considered and addressed the direct effects caused by these pollutants on aquatic organisms.

Contamination of a river with heavy metals may cause effects on the ecological balance of the aquatic environment, and may narrow the diversity of aquatic organisms as the extent of contamination increases (Ayandiran et al. 2009). Khayatzadeh and Abbasi (2010) reported that heavy metals in polluted reservoirs may also affect fish species at the population level.

Stohs and Bagchi (1995) and Leonard et al. (2004) reported that molecular mechanisms of heavy metal cytotoxicity include the following: damage to plasma membranes, binding to proteins and phospholipids, inhibition of Na- &, K-dependent ATPases, inhibition of transmembrane amino acid transport; enzyme inhibition; lipid peroxidation and oxidative DNA damage, along with depletion of antioxidant enzymes via generation of Reactive Oxygen Species (ROS).

Toxicity of Lead to Aquatic Organisms

Lundstedt (2011) reported that lead, a particularly problematic metal, is highly abundant in e-waste. Pb accumulates in the environment and produces both high acute and chronic effects on biological systems (i.e., plants, animals and microorganisms), even at low concentrations (Biesinger et al. 1972; LeBlanc 1982). Lead causes behavioral disturbances, affects survival, growth, learning and metabolism, and inorganic compounds of lead may be carcinogenic (Weber and Dingel 1997; Ribeiro et al. 2009; Huang et al. 2010). Moreover, Pb causes scoliosis in fish (Stomiñska and Jezierska 2000).

Chronic toxicity occurs when lead is bioconcentrated in aquatic species over a period of time, and when it accumulates in internal organs. However, biomagnification has not been observed to occur in the aquatic environment (Prosi 1989). The author noted that the dissolved chemical forms of lead are extremely toxic in the aquatic environment, when present at high concentrations.

When lead concentrations in algae exceed 500 ppb, enzymes needed for photosynthesis are inhibited (Nagpal 1987; Rioboo et al. 2009). When photosynthesis is reduced, algal growth is adversely affected. Decreased algal growth means less food for animals, which has repercussions for the entire ecosystem. Lead also has dire effects on fish. The primary mode of uptake of aqueous Pb^{2+} in freshwater fishes is through their gills into the blood stream (Seymore et al. 1995). Once absorbed, Pb^{2+} is distributed particularly to the liver, kidney, heart and male gonads (ATSDR 2005). When lead concentrations exceed 100 ppb, gill function is affected. Fishes exposed to high levels of lead exhibit a wide-range of effects including muscular and neurological degeneration and destruction, growth inhibition, mortality, reproductive problems, and paralysis (US EPA 1976; Eisler 1988; Rademacher et al. 2003). Acute effects of Pb on freshwater invertebrates (for water exposures and food chain exposures) are normally reported at concentrations of 100–100,000 μg/L (Nagpal 1987; Boyle et al. 2010; Mager et al. 2010, 2011).

Toxicity of Cadmium to Aquatic Organisms

Cd is a nonessential heavy metal and is considered to be one of the most toxic of aquatic contaminants. Cd can cause toxicity to organisms at each biological level, from populations and communities to cellular elements (Rashed 2001). Even at sublethal concentrations, Cd has a cumulative effect and may cause serious disturbances to fish metabolism that produces abnormal behavior, locomotor anomalies or anorexia (Bryan et al. 1995; Cicik and Engin 2005). Hayat et al. (2007) noted that long-term exposure (20 days or more) of juvenile and adult rainbow trout, *Oncorhynchus mykiss,* to waterborne cadmium at sub-lethal concentrations resulted in decreased growth. It is reported that Cd primarily accumulates in fish in the liver, stomach and gills (Abu Hilal and Ismail 2008). Solomon (2008) stated that Cd impairs aquatic plant growth and thus, adversely affects the entire aquatic ecosystem, since green plants are at the base of all food chains.

4.2 Effects of Organic Pollutants on Aquatic Life

Toxicity of PBDEs to Aquatic Organisms

PBDEs are of significant environmental concern because they are toxic, bio-accumulative and persistent (Michigan Department of Environmental Quality 2007). In particular, it was observed in OECD testing that these compounds are not naturally biodegradable (EU draft RAR 2000). They easily bio-accumulate in fatty tissues and bio-magnify throughout food chains (Law et al. 2006). Wollenberger et al. (2005) reported the PBDEs to be very toxic to aquatic organisms. However, current knowledge concerning their effects on aquatic organisms is limited (Breitholtz and Wollenberger 2003; Tam et al. 2012).

Nevertheless, we note that adverse effects on neurobehavioral development (Branchi et al. 2005) and endocrine disruption (Muirhead et al. 2006) have been reported in the literature for PBDE compounds. PBDEs are known to cause many deformities in aquatic organisms, and these morphological abnormalities are more pronounced during embryogenesis (Lema et al. 2007). Specifically, Mhadhbi et al. (2010) observed abnormal skeletal formations and pericardial edema in turbot. These authors also noted that PBDEs are teratogenic to the embryo–larval stages, during which embryo development is adversely affected, perhaps leading to embryo mortality.

Toxicity of the PCDD/Fs to Aquatic Organisms

The polychlorodibenzodioxins and furans (PCDD/Fs) are persistent organic pollutants displaying high toxicity and bioaccumulation potential (US EPA 2000). They tend to biomagnify in higher trophic levels of the aquatic food web. In a study conducted for the Ontario Ministry of the Environment, the authors noted that because PCDD/Fs are hydrophobic, the majority of them released into aquatic systems tend to bind to the organic fraction of suspended and/or bed sediments (Dillon Consulting Limited 2007). They also have an affinity for lipid-rich tissues of aquatic organisms. According to the Canadian Council of Ministers of the Environment (2001), aquatic organisms may either take up PCDD/Fs from water or sediment, or by consuming contaminated prey.

In fish, PCDD/Fs are thought to elicit most, if not all, of their toxic and biochemical effects via the aryl hydrocarbon (Ah) receptor (Environment Canada 2000). The adverse consequences of PCDD/Fs on fish are primarily manifested as reproductive effects such as survival of eggs and embryos (Dillon Consulting Limited 2007). As a result, the long-term population of local species is negatively affected. The authors noted that PCDD/Fs also affect the survival, growth and reproduction of adult fish.

5 Summary

The volume of e-waste is growing around the world, and, increasingly, it is being disposed of by export from developed to developing countries. This is the situation in Ghana, and, in this paper we address the potential consequences of such e-waste disposal. Herein, we describe how e-waste is processed in Ghana, and what the fate is of e-waste-chemical contaminants during recycling and storage. Finally, to the extent it is known, we address the prospective adverse effects of e-waste-related contaminants on health and aquatic life downstream from a large e-waste disposal facility in Accra, Ghana.

In developing countries, including Ghana, e-waste is routinely disassembled by unprotected workers that utilize rudimentary methods and tools. Once disassembled, e-waste components are often stored in large piles outdoors. These processing and storage methods expose workers and local residents to several heavy metals and organic chemicals that exist in e-waste components. The amount of e-waste dumped in Ghana is increasing annually by about 20,000 t. The local aquatic environment is at a potential high risk, because the piles of e-waste components stored outside are routinely drenched or flooded by rainfall, producing run-off from storage sites to local waterways. Both water and sediment samples show that e-waste-related contaminants have entered Ghana's water ways.

The extent of pollution produced in key water bodies of Ghana (Odaw River and the Korle Lagoon) underscores the need for aquatic risk assessments of the many contaminants released during e-waste processing. Notwithstanding the fact that pollutants from other sources reach the water bodies, it is clear that these water bodies are also heavily impacted by contaminants that are found in e-waste. Our concern is that such exposures have limited and will continue to limit the diversity of aquatic organisms. There have also been changes in the abundance and biomass of surviving species and changes in food chains. Therefore, the need for actions to be taken to reduce entry of e-waste pollutants into Ghana's aquatic environment is real and is immediate.

Heavy metals (e.g., lead, cadmium, copper and zinc) and organic pollutants (e.g., PCDD/Fs and PBDEs) have been detected in the sediments of local water bodies in quantities that greatly exceed background levels. This fact alone suggests that aquatic organisms that live in the affected water bodies are highly exposed to these toxic, bio-accumulative, and persistent contaminants. These contaminants have been confirmed to result from the primitive methods used to recycle and process e-waste within the local environment.

Only limited local data exist on the threats posed by these e-waste-related contaminants on nearby natural resources, especially aquatic organisms. In this review, we have addressed the potential toxicity of selected heavy metals and organic pollutants on aquatic organisms. Since there are no data on concentrations of contaminants in the water column, we have based our predictions of effects on pollutant release rates from sediments. Pollutants that are attached to sediments are routinely released into the water column from diffusion and advection, the rate of which depends on pH and Eh of the sediments. E-waste contaminants have the potential to produce deleterious effects on the behavior, physiology, metabolism, reproduction, development and growth of many aquatic organisms. Because it is confirmed that both heavy metal and organic contaminants are reaching the biota of Ghana's local waterways, we presume that they are producing adverse effects. Because local data on the aquatic toxicity of these contaminants are as yet unavailable, we strongly recommend that future research be undertaken to examine, on a large scale and long-term basis, both contamination levels in biota, and adverse effects on biota of the nearby water bodies.

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