E-waste: An assessment of global production and environmental impacts

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Abstract

E-waste comprises discarded electronic appliances, of which computers and mobile telephones are disproportionately abundant because of their short lifespan. The current global production of E-waste is estimated to be 20–25 million tonnes per year, with most E-waste being produced in Europe, the United States and Australasia. China, Eastern Europe and Latin America will become major E-waste producers in the next ten years. Miniaturisation and the development of more efficient cloud computing networks, where computing services are delivered over the internet from remote locations, may offset the increase in E-waste production from global economic growth and the development of pervasive new technologies. E-waste contains valuable metals (Cu, platinum group) as well as potential environmental contaminants, especially Pb, Sn, Hg, Cd, Ni, polybrominated diphenyl ethers (PBDEs), and polychlorinated biphenyls (PCBs). Burning E-waste may generate dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), polyhalogenated aromatic hydrocarbons (PHAHs), and hydrogen chloride. The chemical composition of E-waste changes with the development of new technologies and pressure from environmental organisations on electronics companies to find alternatives to environmentally damaging materials. Most E-waste is disposed in landfills. Effective reprocessing technology, which recovers the valuable materials with minimal environmental impact, is expensive. Consequently, although illegal under the Basel Convention, rich countries export an unknown quantity of E-waste to poor countries, where recycling techniques include burning and dissolution in strong acids with few measures to protect human health and the environment. Such reprocessing initially results in extreme localised contamination followed by migration of the contaminants into receiving waters and food chains. E-waste workers suffer negative health effects through skin contact and inhalation, while the wider community are exposed to the contaminants through smoke, dust, drinking water and food. There is evidence that E-waste associated contaminants may be present in some agricultural or manufactured products for export.

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Waste Electrical and Electronic Equipment
Electronic waste
Recycling
Waste management

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1. Introduction

E-waste and Waste Electrical and Electronic Equipment (WEEE) describe discarded appliances that use electricity. E-waste describes waste electronic goods, such as computers, televisions and cell phones, while WEEE also includes traditionally non-electronic goods such as refrigerators and ovens. Table 1 lists some common WEEE items.

The distinction between E-waste and WEEE is becoming less sharp due to the advent of pervasive computing (Kohler and Erdmann, 2004), where programmable microprocessors are incorporated into electrical equipment, such as refrigerators, which are not normally considered electronic items (Hilty, 2005). However, it is the rapid growth of computing that is driving E-waste production. In the next five years, one billion computers will be retired (Ladou and Lovegrove, 2008).

E-Waste is chemically and physically distinct from other forms of municipal or industrial waste; it contains both valuable and hazardous materials that require special handling and recycling methods to avoid environmental contamination and detrimental effects on human health. Recycling can recover reusable components from municipal or industrial waste; it contains both valuable and

The environmental effects of E-waste disposal are drawing increasing attention from politicians, Non Governmental Organisations (NGOs) such as Greenpeace (www.greenpeace.org), the Basel Action Network (www.ban.org), the Silicon Valley Toxics Coalition (www.svtc.org), as well as the scientific community. As of June 2006, there were more than 500 scientific articles dealing with E-waste and its environmental effects.

This review aims to assess the global production of E-waste, the contaminants and contaminant fluxes associated with E-waste, and the likely environmental impact of E-waste associated contaminants. This paper focuses on the physical, chemical and environmental effects of E-waste, rather than E-waste associated politics, which are discussed extensively in publications from the aforementioned NGOs.

2. The current and future global production of E-waste

In 2006, the world’s production of E-waste was estimated at 20–50 million tonnes per year (UNEP, 2006), representing 1–3% of the global municipal waste production of 1636 million tonnes per year (OECD, 2008). Cobbing (2008) calculated that computers, mobile telephones and television sets would contribute 5.5 million tonnes to the E-waste stream in 2010, rising to 9.8 million tonnes in 2015. In rich countries, E-waste may constitute some 8% by volume of municipal waste (Widmer et al., 2005).

The contribution of an item to the annual E-waste production, $E$ (kg/year) depends on the mass of the item, $M$ (kg), the number of units in service, $N$, and its average lifespan, $L$ (years) [1].

$$E = \frac{MN}{L}$$  \hspace{1cm} (1)

Computers, which have an average lifespan of three years (Betts, 2008a), comprise a greater proportion of WEEE than refrigerators and ovens, which have lifespans of 10–12 years. Table 1 provides a list of some WEEE items along with their mass and expected lifetimes.

2.1. An estimation of global E-waste production

Calculating global E-waste production requires information on the number of items in service. These data are generally available in rich countries so E-waste production can be calculated using Eq. (1). Switzerland produces 9 kg per person per year (Sinha-Khetriwal et al., 2005). Europeans produce E-waste at a rate of 14 kg per person per year (Goosney, 2004), making a total annual E-waste production for the 15-member-state European Union (EU-15) of 5.5 million tonnes per year, and the EU-27 of 8.3–9.1 million tonnes per year (Huisman and Magalini, 2007). The United States produced some 2.63 million tonnes in 2005 (Cobbing, 2008), while China produced 2.5 million tonnes (Liu et al., 2006). E-waste production data for poorer countries are less readily available. India and Thailand are estimated to have, respectively, produced just 0.33 and 0.1 million tonnes of E-waste in 2007 (Cobbing, 2008).

Summing the available data indicates that the global production of E-waste was at least 13.9 million tonnes per year in the middle of this decade. This figure does not include Latin America, Africa, Canada or Russia and does not account for the growth in the last four years.

An independent estimation was obtained using Eq. (1) using data from Table 1 and data for the total number of computers (0.78 bn [2004]), mobile telephones (3.4 bn [2007]), fixed-line telephones (1.2 bn [2005]), televisions (1.4 bn [2003]), and radios (2.5 bn [2003]) (Nationmaster, 2009). The total E-waste production, 11.7 million tonnes

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### Table 1

List of common Waste Electrical and Electronic Equipment (WEEE) items, including those normally considered as E-waste.

<table>
<thead>
<tr>
<th>Item</th>
<th>Wt of Item (kg)</th>
<th>Typical life (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WEEE normally considered E-waste</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>Facsimile machine</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>High-fidelity system</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Mobile telephone</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Electronic games</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Photocopier</td>
<td>60</td>
<td>8</td>
</tr>
<tr>
<td>Radio</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Television</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Video recorder and DVD player</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>WEEE not normally considered E-waste</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air conditioning unit</td>
<td>55</td>
<td>12</td>
</tr>
<tr>
<td>Dish washer</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>Electric cooker</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>Electric heaters</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Food mixer</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Freezer</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>Hair dryer</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Iron</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Kettle</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Microwave</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>Telephone</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Toaster</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Tumble dryer</td>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>Vacuum cleaner</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Washing machine</td>
<td>65</td>
<td>8</td>
</tr>
</tbody>
</table>

---

$a$ (Betts, 2008a).
$b$ (Cobbing, 2008).
$c$ (Li et al., 2009).
per year, is similar to the above calculation of the E-waste produced in rich countries. Again, the total global E-waste production will be considerably higher because some of the data are six years old. Similarly, the mass of WEEE produced will be higher because it includes heavy electrical items, such as refrigerators and air conditioning units.

Adjusting the calculated figure of 13.9 million tonnes per year for the 20% growth in the World’s Gross Domestic Product (GDP) over the last five years, gives 16.8 million tonnes. Given that computers form the bulk of E-waste and that most E-waste is produced in rich countries (Cobbing, 2008), it is probable that the actual global E-waste production is 20–25 million tonnes per year, at the lower end of the United Nations Environment Programme’s (UNEP’s) estimation of 20–50 million tonnes per year (UNEP, 2006).

2.2. Future trends in E-waste production

The global production of E-waste will change as economies grow and new technologies are developed. For any given country, the total number of computers and other potential E-waste items is strongly correlated with the country’s GDP, because electrical and electronic items are essential for the functioning of all but the most primitive economies. Fig. 1 shows the total number of computers per country as a function of that country’s GDP. Fig. 1 supports the supposition that economic growth will result in more E-waste production. However, assessing the effect of economic growth on the total E-waste production from Fig. 1 is difficult because there is considerable scatter and no weighting according to the country’s population. A better measure of the distribution of computers, and by implication E-waste production, is their distribution amongst the Earth’s population as a function of wealth (Fig. 2), defined here as GDP per person weighted for Purchasing Power Parity (PPP). Fig. 2 shows that there is an exponential relationship between wealth and number of computers and that the richest billion people have 75% of all computers. Fig. 2 indicates that the number of computers per 100 people, and hence the total number of computers, will increase faster in richer countries than in poor countries for any given increase in GDP. This is in agreement with the predictions of Hischier et al. (2005), who reported that the annual growth of E-waste in Europe is increasing at a rate of 3–5%, compared to an average (2005–2008) increase in GDP of 2.6%. If the number of computers is indicative of total E-waste production, then Eastern Europe, Latin America and China will become major E-waste producers in the next 10 years.

Changes in technology will also affect the global mass of E-waste produced. Short innovation cycles of hardware have led to a high turnover of devices. The lifespan of central processing units in computers dropped from 4–6 years in 1997 to 2 years in 2005 (Babu et al., 2007).

The average mass of 25 kg for a personal computer (Table 1) is indicative of a desktop computer with a Cathode Ray Tube (CRT) monitor, which represents most of the past and present computers in the E-waste stream. However, the advent of Liquid Crystal Displays (LCD) will reduce the average weight of a desktop. More significantly, the increasing prevalence of laptop and netbook computers (Micklethwait, 2009b), which weigh just 1–3 kg, will significantly reduce the average mass of a discarded computer. In the case of netbooks, computing power and associated potential E-waste production has been shifted from the end user to remote computing “clouds”, supported by warehouses of shared machines, which may be located in another country (Micklethwait, 2009b). There is a lacuna of information on E-waste generation from these computing warehouses. E-waste growth from increasing wealth and shorter innovation cycles may be offset by miniaturisation and outsourcing of computing power.

3. Potential environmental contaminants associated with E-waste

The chemical composition of E-waste varies depending on the age and type of the discarded item. However, most E-waste is composed of a mixture of metals, particularly Cu, Al, and Fe, attached to, covered with, or mixed with various types of plastics and ceramics (Hoffmann, 1992). A discarded personal computer with a CRT monitor typically weighs 25 kg and consists of metal (43.7%), plastics (23.3%), electronic components (17.3%) and glass (15%) (Berkhout and Hertin, 2004). Heavy WEEE items, such as washing machines and refrigerators, which are mostly composed of steel, may contain fewer potential environmental contaminants than lighter E-waste items, such as laptop computers, which may contain high concentrations of flame retardants and heavy metals.

Virtualiy all E-waste contains some valuable components or base materials, especially Cu. These are environmentally important, because they provide an incentive for recycling, which occurs predominantly in poor countries, and may result in a human health risk or environmental pollution. Platinum group metals are included in electrical contact materials due to their high chemical stability and conductance of electricity. The precious metal concentrations in
printed circuit boards is more than tenfold higher than commercially-mined minerals (Betts, 2008a).

Table 2 lists the potential environmental contaminants associated with E-waste. Some contaminants, such as heavy metals, are used in the manufacture of electronic goods, while others, such as polychlorinated aromatic hydrocarbons (PAHs) are generated by the low-temperature combustion of E-waste. The burning of insulated wire, which typically occurs in open iron barrels, generates 100 times more dioxins than burning domestic waste (Gullett et al., 2007).

The concentrations of environmental contaminants found in E-waste depend on the type of item that is discarded and the time when that item was produced. E-waste composition is spatially and temporally heterogeneous. Table 2 gives the concentrations of some components in Swiss E-waste (Morf et al., 2007). Concentrations of Cd, Cu, Ni, Pb and Zn are such that were these elements released into the environment they would pose a risk to ecosystems and human health (Wilmoth et al., 1991). Using the estimation that 20 million tonnes of E-waste are produced annually, combined with the data of Morf et al. (2007), the amounts of some potential contaminants that are contained in the annual E-waste stream have been calculated (Table 2). Although recycling may remove some contaminants, large amounts may still end up concentrated in landfills or E-waste recycling centres, where they may adversely affect human health or the environment. Some 820,000 t of Cu are included in the annual flow of E-waste. Despite recycling, it would seem E-waste is a major contributor to the some 5000 t of Cu emitted into the environment annually (Bertram et al., 2002).

Polybrominated diphenyl ethers (PBDEs) are flame retardants that are mixed into plastics and components. There are no chemical bonds between the PBDEs and the plastics and therefore they may leach from the surface of E-waste components into the environment (Deng et al., 2007). PBDEs are lipophilic, resulting in their bioaccumulation in organisms and biomagnification in food chains (Deng et al., 2007). PBDEs have endocrine disrupting properties (Tseng et al., 2008). Obsolete refrigerators, freezers and air conditioning units contain ozone-depleting Chlorofluorocarbons (CFCs). These gases may escape from items disposed in landfills (Scheutz et al., 2004).

3.1. Unusual contaminants in E-waste

E-waste may contain complex mixtures of potential environmental contaminants that are distinct from other forms of waste. Some potential contaminants in E-waste are uncommon, even in other contaminated sites. Consequently, there has been little work on their environmental effects. Examples include Li (batteries), Be (contact material), Sb (flame retardant) (Ernst et al., 2003), and Ga and In (used in Si chips and LCD monitors) (Ladou and Lovegrove, 2008).

3.2. Changing nature of E-waste

E-waste composition is changing with technological development and pressure on manufacturers from regulators and NGOs. The replacement of CRT monitors with LCD displays will reduce the concentration of Pb in E-waste, as each CRT tube contains some 2 kg Pb (Puckett et al., 2005). However, LCD displays contain Hg (Mester et al., 2005), In, Sn and Zn (Li et al., 2009). Similarly, fibre optics, which may replace some Cu wires (Berkhout and Hertin, 2004), can contain F, Pb and Zr (Kogo et al., 1995). Rechargeable battery composition has also changed dramatically, from old Ni–Cd, to Ni metal hydrides, to Li ion batteries.

NGOs have placed pressure on manufacturers to reduce or eliminate the content of potential environmental contaminants in their products. Manufacturers are competing to be seen as “green” and want to remove as many toxic chemicals from products as possible (Betts, 2008b). Many producers of electronic and electrical goods have responded to pressure from NGOs and the public and are investigating innovative ways to enhance safe disposal and recycling. For example, radio frequency identification tags cost 10–20 cents and...
provide information about the condition and composition of computer systems and other electronics products (Betts, 2008a). Such tags can alert waste managers and recyclers to valuable components and potential environmental contaminants contained within the end-of-life product (Binder et al., 2008).

Producing halogen-free components would reduce polychlorinated biphenyls (PCBs) and dioxin loadings in E-waste; however, their production is more environmentally costly (Bergendahl et al., 2004). Brominated flame retardants can be replaced with more environmentally friendly phosphorus-based retardants (Dietz et al., 2004) such as aminophenyl phosphate (Mauerer, 2005). Lead-free solder could significantly reduce the environmental burden of this toxic heavy metal (Bradley, 2003); this may be enshrined in law (Herat, 2008) in many countries. In 2003, the European Union enacted the Restriction on Hazardous Substances Directive (RoHS), limiting the concentrations in homogeneous electronic materials of Pb, Hg, Cr (IV), polybrominated biphenyls (PBBS) and PBDEs to 1000 mg/kg, and Cd to 100 mg/kg (LaDou, 2006). RoHS was met with some resistance by manufacturers due to compliance costs and technical problems, such as the use of low-Pb solders that are prone to “tin whisker” growth (Puttlitz and Galyon, 2007).

4. The flux of these contaminants on a global scale: the fate of E-waste

Most E-waste is not recycled, because E-waste items tend to go out with household waste and receive no special treatment (Ladou and Lovegrove, 2008). Of that which is collected, some 80% is exported to poor countries (Schmidt, 2006). Electronic equipment that is no longer of use to the original purchaser may be reused, effectively extending its lifespan. Reuse is ultimately the source of some E-waste in many poor countries (Puckett et al., 2005) that accept donations of equipment considered obsolete in rich countries. Old yet functional electronic equipment is often shipped to developing countries by well-meaning donors in the West. Unscrupulous organisations in rich countries use donations of obsolete electronic equipment as a loop-hole in the Basel Convention to export both functioning and non-functioning electronic equipment (Ladou and Lovegrove, 2008). Brokers who arrange the export of functioning products often pad shipping containers with irreparable waste, which may account for up to 75% of deliveries. Most of this ends up in landfills and informal dumps (Schmidt, 2006).

China receives some 70% of all exported E-waste (Liu et al., 2006), while significant quantities are also exported to India, Pakistan, Vietnam, the Philippines, Malaysia, Nigeria and Ghana (Puckett et al., 2005), and possibly to Brazil and Mexico. Due to the semi-clandestine nature of these operations, the actual mass of E-waste being exported is impossible to quantify. Some 500 shipping containers filled with electronic items pass through Lagos each month (Schmidt, 2006). NGOs such as Greenpeace campaign against this “hidden flow” of E-waste (Cubbing, 2008).

5. Disposal and recycling of E-waste and associated environmental contamination

Most E-waste is currently landfilled (Barba-Gutierrez et al., 2008). Using the Toxicity Characteristic Leaching Procedure (TCLP) (USEPA, 2000), Spalvins et al. (2008) concluded that E-waste disposal in modern-municipal solid waste landfills is unlikely to result in lead leachate concentrations of regulatory concern. However, Dagan et al. (2007) demonstrated that the chemical cocktail that leached from a variety of consumer electronics using TCLP was toxic to aquatic organisms. Incineration prior to landfilling may increase the mobility of heavy metals, particularly Pb (Gullett et al., 2007). On average the plastic fraction of E-waste has Sn, Pb, Ni, Zn and Sb concentrations >1000 mg/kg as well as >100 mg/kg Cd (Morf et al., 2007). While contained in a plastic matrix, these elements do not leach and are not bioavailable. However, combustion or dissolution will liberate these elements. As with other materials, leaching of many heavy metals such as Pb from E-waste is increased at low pH and in the presence of organic ligands (Jang and Townsend, 2003).

Most studies investigating leaching from landfilled E-waste have investigated just a few key contaminants, especially Pb. However, there is a lacuna of information on the behaviour of oxygenation forming contaminants such as Sb, which can occur at concentrations >1000 mg/kg in some E-waste components (Morf et al., 2007). Antimonate (Sb(OH)₆⁻) has been shown to be more mobile and more toxic in soil than Pb, and is more soluble at higher pH values and readily taken up by plants (Tschan et al., 2009).

Niu and Li (2007) showed that compaction of E-waste, prior or during landfilling, can increase leaching through the disruption of circuit board components. The same authors showed that cement solidification, which imparts impact resistance, raises pH and reduces water flux through the waste, reduced Pb leaching from E-waste to below regulatory levels.

5.1. Recycling

E-waste recycling involves the disassembly and destruction of the equipment to recover new materials (Cui and Zhang, 2008). Recycling can recover 95% of the useful materials from a computer and 45% of materials from cathode ray tube monitors (Ladou and Lovegrove, 2008). In rich countries, such as Japan, high tech recycling operations function well with little environmental impact (Aizawa et al., 2008). Modern techniques can recover high-Pb glass from discarded CRT with minimal environmental impact (Andresola et al., 2007). Any ecological benefits of recycling are more than offset if the waste has to be transported long distances due to the negative environmental effects of fossil fuel combustion (Barba-Gutierrez et al., 2008). However, recycling always has a lower ecological impact than landfilling of incinerated E-waste (Hirschier et al., 2005).

Mechanical separation of components is the first step in E-waste recycling. Components may be separated for reuse or metallurgical processing (He et al., 2006). This process can be automated or carried out by hand. In poor countries, there is a risk that children may be employed to separate E-waste components (Ladou and Lovegrove, 2008). An open flame is often used to free components (Manomaivibool, 2009), which may result in exposure to volatilised contaminants.

Valuable metals may be recovered from E-waste by pyro- hydro- and bio-metallurgical processes (Cui and Zhang, 2008). Pyrometallurgical processing includes incineration of the matrix and smelting of the target metals. The efficacy of this process depends on investment. Shoddy operations have the potential to emit dangerous compounds into the environment. Copper is a catalyst for dioxin formation when flame retardants are incinerated, in particular the low-temperature incineration of brominated flame retardants (Cui and Zhang, 2008). Hydro- metallurgical processes involve the dissolution and recovery of the target metals with acids, cyanide, halides, thiourea or thiosulphate.

Presently limited to rich countries, bio-metallurgical processing is attractive due to its low-cost and high specificity for the target elements (Cui and Zhang, 2008). Brandi et al. (2001) showed how Thiobacillus bacteria and fungi (Aspergillus niger, Penicillium simplicissimum) could facilitate metal leaching from electronic scrap. Creamer et al. (2006) employed Desulfovibrio desulfuricans to recover Au, Pt and Cu from E-waste.

6. Environments contaminated by E-waste

6.1. Case study: Guiyu and some other E-waste recycling centres

The city of Guiyu with its surrounding towns in the Guangdong region of China is the largest E-waste recycling site in the world.
Recycling has been occurring since 1995 (Wong et al., 2007). Guiyu has a population of 150,000, most of which are immigrants. Nearly 80% of families have members who have engaged in E-waste recycling operations (Li et al., 2008a). Wind carries particulate matter from Guiyu to the Pearl River Delta Region, which has a population of some 45 million people (Deng et al., 2007). Villagers and migrant workers use environmentally unsound techniques to recycle E-waste. These include the heating and manual removal of components from printed circuit boards, open burning to reduce volumes and recover metals, and open acid digestion of E-waste to recover precious metals. The waste-acid, rich in heavy metals, is then discarded onto the soil or into waterways. Solder is melted from printed circuit boards over makeshift coal grills. Portable household fans are the only precautionary measures taken to reduce worker exposure to toxic solder fumes (Leung et al., 2008). Workers toil without goggles, masks or gloves (Li et al., 2008a). These crude recycling techniques have resulted in widespread environmental contamination with some of the components listed in Table 2.

6.2. Waters and aquatic systems

E-waste contaminants can enter aquatic systems via leaching from dumpsites where processed or unprocessed E-waste may have been deposited. Similarly, the disposal of acid following hydrometallurgical processes into waters or onto soils, as well as the dissolution or settling of airborne contaminants, can also result in the contamination of aquatic systems. Luo et al. (2007b) reported that carp from the Nanyang river, near Guiyu, were bioaccumulating PBDEs to concentrations of up to 766 ng/g (fresh weight). Unsurprisingly, the same authors (Luo et al., 2007a) reported elevated PBDE concentrations in the sediments (up to 16,000 ng/g) of the same river. In an aquatic ecosystem near an E-waste recycling plant, Wu et al. (2008) reported that the water snake, the top predator, had on average 16,512 ng/g PCBs and 1091 ng/g PBDEs on a wet weight basis. Mud carp, crucian carp and prawns from the same area also had elevated concentrations of these contaminants. The ambient water contained just 204 ng/L PCBs. Waterfowl from downstream areas in the Pearl River Delta also contained elevated PCB and PBDEs (Luo et al., 2009a). Brominated flame retardants other than PBDE, namely 1,2-bis(2,4,6-tribromophenoxy)ethane, decabromodiphenyl ethane and tetrabromobisphenol A bis (2,3-dibromopropyl) ether, are widespread in various biota of the Pearl River Delta, downstream from an E-waste recycling town (Shi et al., 2009).

Wang and Guo (2006) found up to 0.4 mg/L Pb in river water downstream of a recycling plant in Guiyu, some 8 times higher than the local drinking water standard (0.05 mg/L). Similarly, Wong et al. (2007) reported elevated concentrations of Ag, Cr, Li, Mo, Sb and Se in the nearby Lianjiang river.

6.3. Air

Many E-waste contaminants are spread into the air via dust. This is a major exposure pathway for humans through ingestion, inhalation and skin absorption (Mielke and Reagan, 1998). Air samples taken near Guiyu contained polychlorodibenzo-p-dioxins between 65 and 2765 pg/m³, the highest level of atmospheric dioxins ever reported (Li et al., 2007).

Combustion of E-waste containing flame retardants has resulted in concentrations of total PBDEs of up to 16,575 pg/m³ in aerial samples near Guiyu, some 300 times higher than in nearby Hong Kong (Deng et al., 2007). Aerial contamination of PBDEs in the city of Guiyu exceeds 11,000 pg/m³ during the daytime, dropping to under 5000 pg/m³ at night (Chen et al., 2008a). Similarly, high aerial concentrations of particulate PAHs, Cr, Cu and Zn have also been reported (Deng et al., 2006). Leung et al. (2008) reported concentrations of over 2% Pb and several thousand mg/kg Cu and Zn in dust the roads in Guiyu. Dust collected from E-waste recycling workshops had Pb, Cu and Zn concentrations some fivefold higher than road dust. Ha et al. (2009) showed that E-waste workers in Bangalore breathed dust-laden air containing Cd, In, Sn, Sb, Pb and Bi at concentrations of 1.5, 1.3, 91, 13, 89 and 1.0 ng/m³ respectively.

6.4. Soils and terrestrial environments

Soils from a site where acid leaching was used to recover valuable metals, contained up to 4250 ng/g PBDEs (Leung et al., 2007). There are elevated concentrations of PCBs, PAHs (Shen et al., 2009a) and PBDEs (Cai and Jiang, 2006) in Chinese agricultural soils proximal to E-waste reprocessing sites. Luo et al. (2009b) reported PBDE concentrations of 191 to 9156 ng/g (dry weight) in farmland soils 2 km from an E-waste recycling workshop. Soils from this region also contain polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), PCBs and PAHs at concentrations up to 100, 330 and 20,000 ng/g, respectively (Shen et al., 2009b).

Liu et al. (2008) reported elevated concentrations of PBDEs and PCBs in soils, plants and snails from the town of Guiyu and the surrounding areas. PBDEs are translocated from soils to plants. Leaves of bracken fern (Pteridium aquilinum L.), spider fern (Pteris multifida Poir.), sorghum (Sorghum bicolor L.), Japanese dock (Rumex japonicus Houtt.) and Eastern daisy fleabane (Erigeron annuus L.) contained PBDEs at concentrations of 144, 116, 162, 278 and 326 ng/g (dry matter), respectively, when growing in soil containing 25,479 ng/g PBDE (Yang et al., 2008). Although the bioaccumulation coefficients are small (<0.01) plant uptake may facilitate the entry of these contaminants into food chains.

Soils at an E-waste recycling slum in Bangalore contained up to 39 mg/kg Cd, 4.6 mg/kg In, 957 mg/kg Sn, 180 mg/kg Sb 49 mg/kg Hg, 2850 mg/kg Pb, and 2.7 mg/kg Bi (Ha et al., 2009). These concentrations are some one-hundredfold higher than those found at a nearby control site in the same city.

Analysis of rice samples from another E-waste processing town in Eastern China, Taizhou (Zhejiang province) revealed concentrations of Pb and Cd in polished rice to be 2–4 times in excess of 0.2 mg/kg, the maximum allowable concentrations of these elements in foodstuffs in China (Fu et al., 2008). In the same town, Liang et al. (2008) measured elevated levels (up to 18 ng/g) of PBDEs in chicken tissues and concluded that these toxins may pose a threat to humans and ecosystems. Rice paddy soils adjacent to E-waste recycling areas in the Zhejiang province were shown to reduce the germination rate of rice (Zhang and Min, 2009). A micronuclei assay using Vicia fabia indicated that the contaminants in these soils also promote DNA damage.

6.5. Humans

Aerial contamination with dioxins at Guiyu has resulted in levels of human exposure some 15–56 times the WHO recommended maximum intake (Chatterjee, 2007). Elevated levels of dioxins were found in human milk, placentas and hair, indicating that dioxins are being taken up by humans, from the air, water, or foodstuffs, at sufficient levels to pose a serious health risk (Chen et al., 2007).

The transfer of E-waste derived PCBs to ground and surface-waters, agricultural soils, rice, eggs, fish and ultimately humans has been demonstrated (Zhao et al., 2006). E-waste workers and other residents from Guiyu had median blood serum BPDE concentrations of 126 ng/L and 35 ng/L, respectively, compared to referents from a nearby town who had just 10 ng/L (Qu et al., 2007). Samples of human hair from towns near Taizhou contained PBBS, PBDEs and PCBs at concentrations up to 58 ng/g, 30 ng/g and 182 ng/g, respectively (Zhao et al., 2008).

Children in Guiyu had significantly higher blood Pb (Huo et al., 2007; Li et al., 2008b) and Cd (Zheng et al., 2008) levels and lower cognitive abilities than children from a nearby control town (Li et al., 2008).
Similarly, lactating residents of Guiyu had elevated concentrations of PCBs in their breast milk (Xing et al., 2009). This could not be attributed to a single exposure pathway, since people are exposed to PCBs through many enriched foodstuffs, drinking water sources and occasional air contamination.

Li et al. (2008a) reported elevated levels of Cr (median 0.094 mg/L) in umbilical cord blood from infants in Guiyu. Umbilical cord Cr concentrations were correlated with DNA damage and were correlated as well with the mother’s exposure to E-waste recycling. However, it was unclear whether Cr or some other toxic agent associated with E-waste resulted in DNA damage. Liu et al. (2009) reported that E-waste recycling workers from villages in the Jinhua county had chromosomal aberrations at a rate some 20-fold higher than villagers not exposed to E-waste. The authors conclude that E-waste is a potential source of genetic mutation and may induce cytogenetic damage within the general population exposed to E-waste pollution.

7. The re-exportation of contaminants associated with E-waste: the other hidden flow

E-waste recycling as conducted in Guiyu results in the contamination of the entire region, pervading the water, air, soil and biota contained therein. Although exports to poor countries are impossible to quantify, even a small fraction of the global E-waste stream would contribute hundreds of tonnes of Pb and several tonnes of Cd, Hg and PCBs. Therefore, other products that are manufactured in E-waste processing regions may contain elevated levels of E-waste associated contaminants. Some of these products may be consumed locally. However, others may be exported to national or international markets. Weidenhamer and Clement (2007a) found evidence that Pb from E-waste was being incorporated into Chinese-manufactured jewellery for export to the United States. Wipe tests showed that this lead was potentially available for human absorption (Weidenhamer and Clement, 2007b).

Reports abound of children’s toys, imported from China, which contain elevated levels of lead or brominated flame retardants (Chen et al., 2009b). Although the authors did not link the source of the contaminants to E-waste, it is conceivable that recycled materials from E-waste, which may contain PBDEs or PCBs, are used in the manufacture of products for export.

Zhao et al. (2009) found that polyhalogenated aromatic hydrocarbons (PAHs) occurred in elevated concentrations in the foodstuffs produced in an E-waste processing region in the Zhejiang province of China. Ultimately, some of these food products may be exported, posing an international health risk. Regular screening tests may not detect some of the unusual contaminants associated with E-waste. The risk of re-exportation of E-waste contaminants warrants further investigation.

Fig. 3 shows the fluxes of contaminants associated with E-wastes from producers to receivers and ultimately to humans. The fluxes shown in Fig. 3 are relevant at a range of scales, both national and international. Fig. 3 shows that, potentially, E-waste may affect the whole of humanity.

8. Conclusions

E-waste is omnipresent. It is characterised by its unusual chemical composition and the difficulties associated with determining its mass and flux at both local and global scales. Contamination associated with E-waste has already caused considerable environmental degradation in poor countries and negatively affected the health of the people who live there. Cleansing of such large contaminated sites is probably unfeasible, since they have been heavily contaminated with numerous contaminants, many of which are poorly studied. However, the negative effects of the contaminants at these sites may be reduced using standard remediation technologies. There is limited knowledge on the ecological effects, human health risks and remediation options for some E-waste contaminants, such as Li and Sb, since they are not normally environmental pollutants. Rich countries have self-interest in mitigating the negative environmental effects of E-waste because it will negatively affect the quality and quantity of food and manufactured goods that are imported from poor countries.

List of abbreviations

- CFC Chlorofluorocarbon
- CRT Cathode Ray Tube
- GDP Gross Domestic Product
- LCD Liquid Crystal Display
- NGO Non Governmental Organisation
- PAH polycyclic aromatic hydrocarbon
- PBB polybrominated biphenyl
- PBDE polybrominated diphenyl ether
- PCB polychlorinated biphenyl
- PCDD polychlorinated dibenzo-p-dioxin
- PCDF polychlorinated dibenzofuran
- PHAH polyhalogenated aromatic hydrocarbon
- PPP Purchasing Power Parity
- RoHS Restriction on Hazardous Substances Directive
- TCLP Toxicity Characteristic Leaching Procedure
- UNEP United Nations Environment Programme
- WEEE Waste Electrical and Electronic Equipment

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