CHAPTER 3

Toxicology of E-Waste Chemicals—Mechanisms of Action

INTRODUCTION

1. TOXIC METALS/METALLOIDS

Electron waste contains a number of toxic chemicals, which can be divided into metallic elements and organic chemicals. A number of these agents have been extensively studied, and there is solid toxicological database for understanding their potential hazard. Others have not been so well studied, and there is the issue of mixture exposures. Each general category of e-waste chemicals has its own special set of concerns with regard to knowledge base and hence being amenable to mode of action (MOA) risk assessment approaches. This first section of this chapter will focus on toxic metals and metalloids on an individual or compound basis since both may be present in e-waste materials. It should be noted here that some of these elements such as gold and indium are valuable, leading to extensive efforts for their recovery. Other toxic elements such as lead, cadmium, chromium, and arsenic are less valuable and may be released in both occupational exposures and into the general environment. Plastics and organic chemicals in electronic devices, such as those incorporated into electronics as fire retardants, are less valuable and frequently released during the recycling process. This is a particularly important issue in developing countries with limited resources for occupational or environmental protection. Finally, the chapter will attempt to briefly summarize the sources of exposures and mechanisms of toxicity for some of the known major toxic inorganic and organic e-waste chemicals and highlight populations at special risk for toxic outcomes.

1.1 Lead

Lead, with atomic number 82, whose toxic properties have been known for centuries (NAS/NRC, 1993) has been used as shielding in cathode ray tubes (Herat, 2008) and solders for circuit boards (Li, Lu, Guo, Xu, & Zhou, 2007; Suganuma, 2001). Humans could be exposed to lead dust from the destruction of these common e-waste components via lead-containing dust and lead

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fumes from breakage and incineration activities (Wong et al., 2007). This is a particular issue for the fetus, children, and women of childbearing age (Meyer, Brown, & Falk, 2008); however, all age groups and a number of organ systems including the nervous system, kidneys, blood-forming organs, reproductive systems (Needleman, 2004), and the cardiovascular system(Navas-Acien, Guallar, Silbergeld, & Rothenberg, 2007) may be affected. Nutritional status (Hsu & Guo, 2002) and genetic inheritance (Onalaja & Claudio, 2000; Scinicariello, Yesupriya, Chang, & Fowler, 2010) may also play important roles in defining sensitive subpopulations at special risk for toxicity.

The mechanisms of lead toxicity in target organs seem to be complex and markedly influenced by the handling of this element by the skeleton (NAS/NRC, 1993) and intracellular lead-binding proteins (Fowler, 1998) and intranuclear inclusion bodies at elevated exposure levels (Oskarsson & Fowler, 1985a). The biologically available intracellular fraction of lead may interact with a number of organelle systems including the nucleus, mitochondria, and cytosolic fractions (Oskarsson & Fowler, 1985a,b) with resultant perturbations of a number of essential cellular functions (Oskarsson & Fowler, 1985b; Shelton, Todd, & Egle, 1986).

1.2 Cadmium

Cadmium is another toxic element used in semiconductor industry in solders (Dolzhnikov et al., 2015) and more recently in II–VI semiconductor materials (Adachi, 2009). This element has been classified as a Class I carcinogen by IARC (2006) and (Waalkes, 2000) is well known to produce toxicity in kidneys (Nordberg, Fowler, & Nordberg, 2015), the skeleton (Takebayashi, Jimi, Segawa, & Kiyoshi, 2000), and reproductive organs (Akinloye, Arowojolu, Shittu, & Anetor, 2006; Thompson & Bannigan, 2008) via a number of direct and indirect mechanisms (Fowler, 2009; Klaassen, Liu, & Diwan, 2009; Prozialeck, 2000; Waisberg, Joseph, Hale, & Beyersmann, 2003). All age groups may be susceptible but females (Nishijo, Satarug, Honda, Tsuritani, & Aoshima, 2004; Ruiz, Mumtaz, Osterloh, Fisher, & Fowler, 2010; Tellez-Plaza, Navas-Acien, Crainiceanu, Sharrett, & Guallar, 2010; Vahter, Åkesson, Lidén, Ceccatelli, & Berglund, 2007), multiparous postmenopausal women (Bhattacharyya, 1991; Kazantzis, 2004), and the elderly (Fowler, 2013a) seem to be at special risk for adverse outcomes. The cysteine-rich protein metallothionein (MT) plays a major role in the handling of cadmium in tissues. This protein exists as a number of isoforms, which vary between various tissues (Cherian, Jayasurya, & Bay, 2003; Thirumoorthy, Sunder, Kumar, Ganesh, & Chatterjee, 2011). In general, MT appears to modulate both the transport of Cd in the circulation and the intracellular bioavailability of Cd within cells (Squibb, Pritchard, & Fowler, 1984). Once the intracellular binding capacity of MT is exceeded and Cd^{2+} ions are available to interact with sensitive sites, more overt manifestations of cell death are initiated (Squibb et al., 1984).

Cadmium is also a potent initiator of oxidative stress via generation of reactive oxygen species (ROS) (Szuster-Ciesielska et al., 2000; Wang, Fang, Leonard, & Rao, 2004). These ROS are capable of altering normal signaling pathways and produce a number of effects on hormone systems such as those involved in reproduction (Chedrese, Piasek, & Henson, 2006; Safe, 2003; Takiguchi & Yoshihara, 2005). The mechanisms involved in these effects are complex since cadmium itself should not catalyze Fenton chemistry, and hence interference with cellular oxidation/reduction systems and/or depletion of intracellular antioxidant systems are more likely the causes.

1.3 Arsenic

The element arsenic, which is found in a wide variety of electronic devices, is of particular concern, and it is not as valuable as some of the other elements discussed below, so efforts to recover it during recycling are less rigorous. This element, which exists in three main oxidation states (+/−3, +5), may be volatilized by high temperatures creating both potential occupational and environmental hazards (Fawcett & Jamieson, 2011; Henke, 2009). These main oxidation states vary in their acute toxic potential (Fowler, 2013b). In addition, inorganic arsenicals may be methylated to form a variety of methylated species (monomethyl arsenic acids, dimethyl arsenic acids, and trimethyl arsines), which also vary in their relative toxicity (Fowler, 2015; Styblo et al., 2000), and it is possible that intracellular toxicity may be due in part to metabolic interconversions among these methylated species (Aposhian, Zakharyan, Avram, Sampayo-Reyes, & Wollenberg, 2004; Thomas et al., 2007). The mechanisms by which arsenicals produce toxicity seem to be largely centered around effects on inhibition of cellular respiration (Samikkannu et al., 2003) with resultant generation of ROS (Samikkannu et al., 2003). An excess of ROS can in turn produce oxidative stress (Flora, 2011), proteotoxicity (Bolt, Zhao, Pacheco, & Klimecki, 2012; Stanhill et al., 2006), and initiation of apoptotic and necrosis cell death pathways (Bustamante, Nutt, Orrenius, & Gogvadze, 2005) and initiation of arsenic-induced carcinogenesis (Shi, Hudson, & Liu, 2004; Shi, Shi, & Liu, 2004). The combined effects of arsenic with other toxic elements such as gallium and indium in III–V semiconductors such as gallium arsenide and indium arsenide are discussed below.

1.4 Mercury

Mercury is a well-known toxic element that can exist in the 0, +1, or +2 oxidation states and as a number of alkylated forms such as methylmercury, dimethylmercury, and ethylmercury and a number of ring structured forms (Clarkson & Magos, 2006), which vary in their uptake and distribution (Clarkson, Vyas, & Ballatori, 2007). Mercury is used in electronic devices such as flat panel televisions and LCDs (Lim & Schoenung, 2010) and switches (Babu, Parande, &

Basha, 2007) and may be released as Hg^0 vapor during the recycling process. This volatile form may contribute to both occupational exposures during recycling and environmental exposures following microbial methylation reactions (Parks et al., 2013; Ullrich, Tanton, & Abdrashitova, 2001). Methylmercury is the chemical form of greatest environmental concern because of its ability to accumulate in large predator fish species (García-Hernández et al., 2007; Hightower & Moore, 2003; Oken et al., 2003), which can hence lead to human exposures from this food source. The in vivo metabolism of organomercurials is complex and may involve both dealkylation reactions to form inorganic mercury (Suda, Suda, & Hirayama, 1993), which is a potent inducer of MT (Tandon, Singh, Prasad, & Mathur, 2001; Yasutake, Nakano, & Hirayama, 1998), and alkylation reactions mediated by bacterial flora in the microbiome (Betts, 2011; Podar et al., 2015), leading to the formation of methylmercury species. A major point to be noted here is that all of these chemical forms of mercury are toxic to biological systems to some degree. The mechanisms of mercurial toxicity are also complex since these agents may affect a number of essential subcellular systems including the mitochondria (Fowler & Woods, 1977; Lund, Miller, & Woods, 1991), protein synthetic machinery (Nakada, Nomoto, & Imura, 1980; Syversen, 1981; Verity, Brown, Cheung, & Czer, 1977), and cell death pathways (Shenker, Guo, & Shapiro, 1998). The alkylated forms of mercury are a particular problem because of their lipophilic nature and ability to cross cellular and intracellular membranes and penetrate virtually every compartment of the cell (Norseth & Brendeford, 1971).

1.5 Gallium

Gallium is a commonly used element in the production of electronic devices such as computer chips, cellular telephones, and light-emitting diodes (LEDs) (Fowler & Sexton, 2015; Moskalyk, 2003; Rajan & Jena, 2013), and it is recovered as a by-product of aluminum and zinc smelting (Moskalyk, 2003). This element exists in the +3 oxidation state, and metabolism of gallium in vivo seems to be similar to that of iron since administration of gallium interferes with cellular uptake of iron (Seligman, Moran, Schleicher, & David Crawford, 1992) and exerts toxicity by interference with cell cycle division processes (Rasey, Nelson, & Larson, 1981). The mechanisms of gallium toxicity are not well understood, but gallium toxicity induces a specific stress protein response that is different from arsenic or indium toxicity (Aoki, Lipsky, & Fowler, 1990) and includes heme oxygenase 1 and metallothionein-2A apparently via a mechanism involving initial formation of ROS (Yang & Chitambar, 2008). It is also used as an anticancer drug for this reason. This also means that this element, as a potent modulator of important cellular protective mechanisms such as the stress protein response, would have an impact on the stress protein response via concomitant exposure to other elements such as arsenic in gallium arsenide semiconductors (Fowler, Conner, & Yamauchi, 2005, 2008).

This type of interactive elemental information at a basic science level should be incorporated into all risk assessment analyses for semiconductor compounds containing these elements as discussed further below.

1.6 Indium

Indium is another toxic element that is used in a variety of high-speed electronic devices such as cell phones (Silveira, Fuchs, Pinheiro, Tanabe, & Bertuol, 2015), computers (Virolainen, Ibana, & Paatero, 2011), solar cells (Hau, Yip, Zou, & Jen, 2009), and flat panel televisions (Yang, Retegan, & Ekberg, 2013). It is commonly employed in common with arsenic as indium arsenide (Milnes & Polyakov, 1993) or phosphorous as indium phosphide (Metzger, 1996). More recently, gallium indium (GaIn) liquid crystal alloys have permitted the development of soft stretchable electronics (Majidi, Kramer, & Wood, 2011; Tabatabai, Fassler, Usiak, & Majidi, 2013). The production of indium for electronic devices has increased greatly in the past decades and can be expected to increase as it is used in more types of electronic devices. This element is also highly toxic and capable of inhibiting protein synthesis (Aoki et al., 1990) via a mechanism linked to degranulation of the rough endoplasmic reticulum (Fowler, Kardish, & Woods, 1983) and induction of heme oxygenase (HO-1) (Woods, Carver, & Fowler, 1979). As with gallium toxicity noted above, such a compromise protein synthesis exacerbates the toxicity of arsenic or phosphorous by attenuating cellular defense mechanisms against ROS-induced damage to important cellular machinery (Fowler et al., 2005, 2008). Lung disease has also been reported (Tanaka et al., 2010) in workers producing indium phosphide–based flat panel televisions indicating the potential risk of this disorder in persons recycling these devices under less-than-safe work facilities. Indium has been classified as a probable human carcinogen (2A) by IARC (IARC, 2006). NTP chronic inhalation studies (Program, 2001) have reported an increased incidence of lung tumors in both male and female rats and mice. Other studies (Nagano et al., 2011) have also reported an increased incidence of lung tumors in male and female rats but not in mice although clear evidence of pulmonary disease was observed in both species.

1.7 Semiconductor Compounds

1.7.1 III–V Semiconductors

As noted above, a number of electronic devices utilize combinations of gallium, arsenic, and indium as III–V semiconductors to achieve more rapid electronic flows. Combinations of these elements are light emitting and are used to produce LEDs, which are used in a variety of common devices such as clock radios and instrumentation dials (Fowler & Sexton, 2015). It is important to note that respirable particles of such semiconductor compounds will undergo biological attack in the in vivo releasing gallium (Yamauchi, Takahashi, & Yamamura, 1986), indium (Yamauchi, Takahashi, Yamamura, & Fowler, 1992), and arsenic

components. These elements are transported to distant tissues from the site of entry such as the lungs. The arsenic moiety is handled in a manner similar to As^{3+} and excreted in the urine as methylated species (Yamauchi et al., 1986, 1992) following dissolution of the GaAs or InAs moiety.

1.7.1.1 Gallium Arsenide

GaAs, which is used in a variety of instruments including computers, cell phones, and LEDs, is the most well-studied III–V semiconductor with extensive in vivo animal (Goering, Maronpot, & Fowler, 1988; Program, 2000; Tanaka, 2004; Webb, Wilson, & Carter, 1987) and in vitro study data (Burns, Sikorski, Saady, & Munson, 1991; Bustamante, Dock, Vahter, Fowler, & Orrenius, 1997; Sikorski, Burns, Stern, Luster, & Munson, 1991; Webb, Sipes, & Carter, 1984). The overall set of toxic effects seems to be a sum of both chemical toxicities from the Ga and As components following particle degradation in vivo and physical particulate effects that arise from exposure to GaAs particles themselves (Goering et al., 1988). Formation of ROS appears to be an important element in the toxicity of GaAs (Flora, Bhatt, & Mehta, 2009) (Fig 3.1).

1.7.1.2 Indium Arsenide

InAs is also a III–V semiconductor used in a variety of instruments but has a more limited database for both in vitro and in vivo toxicity studies (Bustamante et al., 1997; Conner, Yamauchi, & Fowler, 1995; Omura et al., 2000). Experimental animal studies have shown that particles of respirable dimensions undergo biological attack and partial dissolution in vivo (Yamauchi et al., 1992), resulting in the release of In and As moieties in a manner similar to particles of GaAs. The relative acute toxicity of InAs seems to be greater than that of GaAs on an equivalent dose basis (Fowler et al., 2005, 2008). ROS formation also seems to be a key element in the toxicity of InAs with inhibition of stress protein synthesis as an exacerbating factor adding to overt cell injury/cell death processes (Bustamante et al., 1997).

1.7.1.3 Indium Phosphide

Indium phosphide (InP) is a III–V semiconductor similar to those above and is used in the production of instruments including flat panel television screens and solar cells (Li, Wanlass, Gessert, Emery, & Coutts, 1989). Interstitial lung disease has been reported in workers in plants manufacturing such devices and associated with serum indium concentrations (Chonan, Taguchi, & Omae, 2007; Cummings et al., 2010). In Japanese workers, these lung effects were subsequently reported to occur in a dose-related manner with serum indium concentrations (Nakano et al., 2009). This material is highly toxic and has also been classified as a probable human carcinogen by IARC (2006) on the basis of in vivo animal (Program, 2001) and in vitro cellular studies (Bustamante et al., 1997; Tanaka et al., 1996). The mechanisms of toxicity are also linked to induction of cell death pathways such as apoptosis (Bustamante et al., 1997).

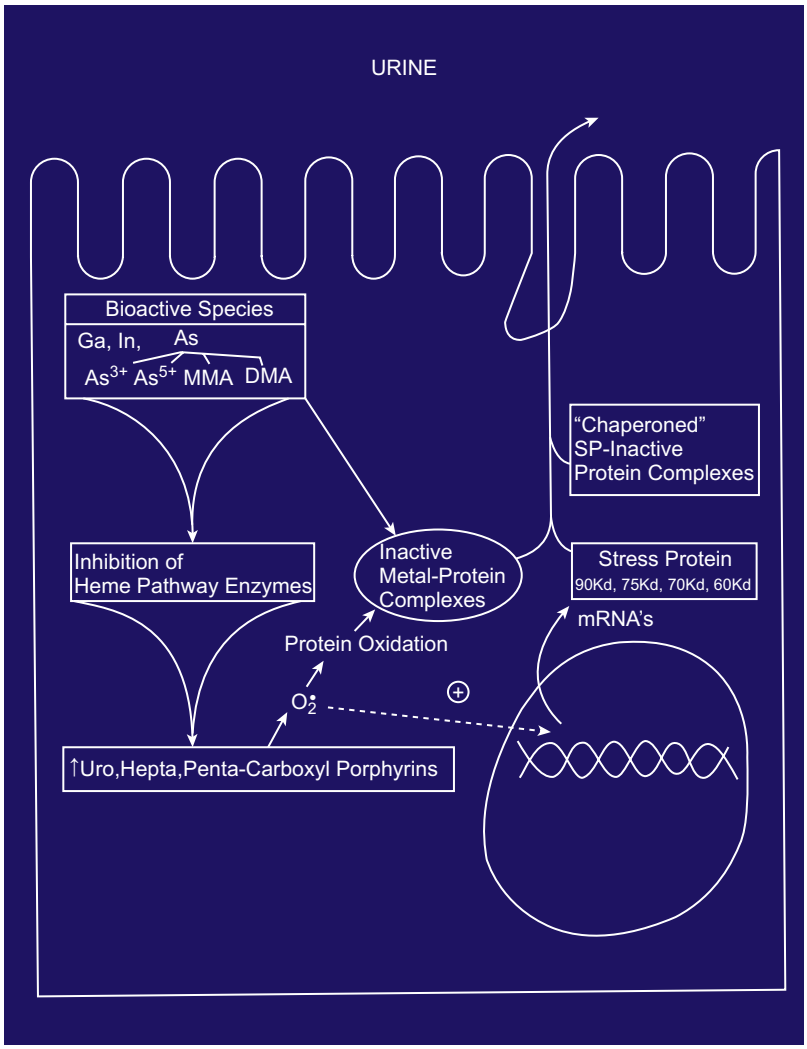

FIGURE 3.1

A global graphic from Fowler et al. (2005) showing intracellular handling and putative mechanisms of toxicity for galium (Ga), indium (In), and arsenic (As) species in a renal tubule cell following release from GaAs or InAs particles. See Fowler et al. (2005, 2008) for details.

1.7.2 II–VI Semiconductors

The II–VI semiconductors represent a second major class of semiconductors with a wide variety of applications in the electronic industry (Afzaal & O'Brien, 2006). Major representatives of this group include cadmium selenide (CdSe), cadmium sulfide (CdS), and cadmium telluride (CdTe). The toxicology database on these materials is limited, but it is reasonable to assume that particles of these materials are handled in vivo in a manner similar to that

of the III–V semiconductors with both particle effects and biological attack releasing Cd^{2+} and Se and S and Te moieties; however, only limited data are available (Kirchner et al., 2005; Wang, Nagesha, Selvarasah, Dokmeci, & Carrier, 2008). In addition, nanoparticles of II–VI semiconductors including CdSe (Sun, Marx, & Greenham, 2003), CdS (Pardo-Yissar, Katz, Wasserman, & Willner, 2003), and CdTe (Kumar & Nann, 2004), among others, have also been formulated for a variety of new technological electronic devices such as solar cells (Kumar & Nann, 2004) that will eventually find their way into the e-waste stream.

1.7.2.1 Cadmium Selenide

Cadmium selenide (CdSe) is a major representative of the II–VI semiconductor group. This material is used in a variety of electronic devices including opto-electronic devices such as blue-green emitters (LEDs), solar cells (Lee, Huang, & Chien, 2008), and infrared (IR) detectors (Li et al., 2005; Nozik et al., 2010; Steckel et al., 2006; Yan, Dadvand, Rosei, & Perepichka, 2010; Zhong, Zhou, Yang, Yang, & Li, 2007). The advent of CdSe nanomaterials further expands the possible uses of these binary compounds in more miniature electronic devices, which will invariably become part the e-waste stream.

1.7.2.2 Cadmium Sulfide

Cadmium sulfide (CdS), known as cadmium yellow, is a bright yellow pigment used in paints and printer inks (Ingrosso et al., 2009; Marjanovic et al., 2011). It has a number of optoelectronic applications (Agarwal & Lieber, 2006; Li et al., 2013). As with CdSe, it is also being incorporated into nanomaterials and hence into electronic devices that will enter the e-waste stream.

1.7.2.3 Cadmium Telluride

Cadmium telluride (CdTe) is mainly used in solar cells but also finds application in IR detectors, radiation detectors, electrooptic modulators (Limousin, 2003; Singh et al., 2004; Su et al., 2010). The recycling of electronic devices such as solar panels whose use is expanding in the global move toward "green energy production" will mean these materials will be entering the e-waste stream in greater quantities in coming decades (Green, Emery, Hishikawa, Warta, & Dunlop, 2015; Sites & Pan, 2007). CdTe nanoparticles are regarded as highly toxic (Cho et al., 2007; Zhang et al., 2007), and the mechanisms of toxicity seem to be linked to the physical properties of the particles and both the Cd and Te components (Cho et al., 2007; Su et al., 2010; Yan et al., 2011). A reasonable concern is that release of CdTe nanoparticles from solid-state materials such as solar panels that could occur during recycling could result in human exposures and subsequent toxicity. The development of nanomaterial forms of CdTe can hence be expected to increase bioavailability in both environmental and occupational exposure terms.

1.7.2.4 Chromium

This metal is found in floppy disks and CDs coated with chromium dioxide (Bhushan, Theunissen, & Li, 1997) and released during the recycling process by shredding or incineration. Chromate (Cr^{6+}) has been identified as a known human carcinogen by the IARC (Boffetta, 1993).

2. ORGANIC CHEMICALS

In addition to a number of toxic metallic compounds that produce both conventional and nanomaterial exposures, electronic devices also contain a number of organic material components. Some of these materials may be released during the recycling process directly into soils in landfills or released into water bodies by runoff from landfills or by aersol exposures from incineration of plastic housings, insulation, or wire coatings (Leung, Cai, & Wong, 2006; Leung, Luksemburg, Wong, & Wong, 2007; Wong et al., 2007). Aerosolized chemicals may also be deposited over wide areas as a result of dry deposition or precipitation with rain (Tian et al., 2011; Zhang, Guan, Li, & Zeng, 2009). Some of the persistent chemicals such as the polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) (Luo, Cai, & Wong, 2007), and polybrominated biphenyls (PBBs) may hence also accumulate in house dust (Wang et al., 2010), fish (Wu et al., 2008), and food crops (Liu et al., 2008; Zhao et al., 2009) in areas impacted by these processes. It is also important to note that these organic chemicals frequently occur as chemical mixtures (Frazzoli, Orisakwe, Dragone, & Mantovani, 2010; Robinson, 2009; Tsydenova & Bengtsson, 2011) both with other organic compounds and the metallic compounds noted above. These combined mixture exposures and employment of child labor greatly complicate risk assessments for chemicals released from e-waste materials (Chan et al., 2007; Wang, Y., Luo, C. L., et al., 2011; Zhang et al., 2014; Zheng et al., 2013). The following discussion is a brief overview of some of the known representative types of organic chemicals associated with e-waste. This is likely not an all-inclusive list but will hopefully give the reader a sense of the general problem area and research needs going forward.

2.1 Styrene

Many electronic devices have plastic components such as composite housings, plastic keyboards, and circuit board frames. Ideally, these plastics may be broken up and recycled into new devices, but frequently this does occur efficiently, and these components may be discarded into landfills or incinerated (Wong et al., 2007). This is frequently the case in developing countries (Nnorom & Osibanjo, 2008). Styrene (acrylonitrile butadiene styrene and high-impact polystyrene) is among the major plastics in e-waste (Brennan, Isaac, & Arnold, 2002) with known toxicity and carcinogenic potential to organs such as the liver (Morgan

et al., 1993) and respiratory tract (Cruzan et al., 2002). Effects on reproductive organs such as the testicular cells have also been reported (Bjørge et al., 1996). This chemical is metabolized via the cytochrome P-450 system (Kim et al., 1997), and toxicity is mediated in part by further Phase II metabolism and conjugation with glutathione (Uusküla, Järventaus, Hirvonen, Sorsa, & Norppa, 1995).

2.2 Bisphenol A

Bisphenol A is another common organic chemical found in e-waste (Huang, Zhao, Liu, & Sun, 2014; Wang & Xu, 2014), which may also persist for prolonged periods in the environment (Huang et al., 2014). It is a known endocrine-disrupting chemical (Rubin, 2011), which has been associated with both reproductive disorders (Kandaraki et al., 2010; Takeuchi, Tsutsumi, Ikezuki, Takai, & Taketani, 2004) and altered glucose regulation (Ropero et al., 2008) and development of type II diabetes (Alonso-Magdalena, Quesada, & Nadal, 2011; Magliano & Lyons, 2012; Sabanayagam, Teppala, & Shankar, 2013). This chemical is of major public health concern (Takayanagi et al., 2006) since it appears to be able to produce effects at relatively low exposure levels (Quesada et al., 2002) via interaction with hormonal receptors (Alonso-Magdalena, Morimoto, Ripoll, Fuentes, & Nadal, 2006). As discussed below, other endocrine-disrupting chemicals associated with e-waste (PCBs and dioxins) may also produce similar effects on glucose regulation leading to obesity and type II diabetes via interaction with the endocrine system (Ruiz, Perlina, Mumtaz, & Fowler, 2016).

2.3 Polychlorinated Biphenyls

PCBs are also known to be present in e-waste (Liu et al., 2008) and to be found at elevated concentrations in air, water, soils, plants, various types of foods, birds, and local residents living near the recycling facility (Luo et al., 2008) in areas near e-waste recycling sites in China (Han et al., 2010; Liu et al., 2008; Luo et al., 2011; Shen et al., 2009; Wang et al., 2012; Zhao et al., 2010). These chemicals are known to induce proliferation of smooth endoplasmic reticulum, induce cytochrome P-450 enzyme activities, and produce hepatotoxic effects (Kasza et al., 1977).

2.4 Polybrominated Biphenyls/Polybrominated Diphenyl Ethers

PBBs and PBDEs are common chemicals used as flame retardants in electronic equipment, and like many halogenated chemicals, they are persistent in the environment and may accumulate in fish (Luo et al., 2007), birds (Luo, Liu, et al., 2009), and crops (Wang, Y., Luo, C., et al., 2011) grown in soils (Luo, Luo, et al., 2009) contaminated with them from landfill or aerosol deposition (Chen et al., 2009). These chemicals produce hepatotoxic and biochemical effects similar to the PCBs as noted above (Kasza et al., 1977).

2.5 Dibenzo Dioxins and Dibenzo Furans

Dibenzo dioxins (DBDs) and dibenzo furans (DBFs) are structurally similar compounds, which have been extensively studied with regard to toxicity and carcinogenicity and as endocrine disrupting agents (Birnbaum, Staskal, & Diliberto, 2003; Van den Berg et al., 2006). Tetrachloro dibenzo dioxin (TCDD) is regarded as among the most toxic man-made chemicals known (Mukerjee, 1998). The DBDs and DBFs are known to be generated by combustion of printed circuit boards (Duan, Li, Liu, Yamazaki, & Jiang, 2011) and removal of polyvinyl chloride insulation from copper wiring by open-pit burning (Man, Naidu, & Wong, 2013; Ren, Tang, Peng, & Cai, 2015).

2.6 Chemical Mixtures and Incineration of Combustion Products

It should be noted that the above short list of chemicals is not inclusive and represents only some of the major toxic organic agents known to be present in the e-waste stream. This list of chemicals does, however, illustrate the need for considering the issue of chemical mixtures in performing risk assessments on e-waste recycling sites since exposure to these chemicals as mixtures is the most common scenario. In addition, there is need to consider combustion products of these agents from open-pit burning. Presently, the number and types of chemical combustion products that would be generated during incineration of e-waste, with the exception of TCDD and BPA, are presently poorly characterized. This is an area of much needed research since it is possible that these incineration by-products (e.g., TCDD and BPA) are also highly toxic and/or carcinogenic. Exposures of persons tending open-pit burn sites or in local communities is a cause for concern. This is particularly true for children who may experience such chemical exposures early in life and develop chronic diseases or cancer as they become adults (Birnbaum & Fenton, 2003). Hazard characterization is an essential first step in conducting a credible risk assessment and of particular importance in dealing with a complex situation detailed in this book for e-waste.

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