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Review article

Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges

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ABSTRACT

Despite regulatory efforts and position papers, electrical and electronic waste (e-waste) remains ill-managed as evidenced by the extremely low rates of proper e-waste recycling (e-recycling) worldwide, ongoing illegal shipments to developing countries and constantly reported human health issues and environmental pollution. The objectives of this review are, first, to expose the complexity of e-waste problems, and then to suggest possible upstream and downstream solutions. Exploring e-waste issues is akin to opening a Pandora's box. Thus, a review of prevailing e-waste management practices reveals complex and often intertwined gaps, issues and challenges. These include the absence of any consistent definition of e-waste to date, a prevalent toxic potential still involving already banned or restricted hazardous components such as heavy metals and persistent and bioaccumulative organic compounds, a relentless growth in e-waste volume fueled by planned obsolescence and unsustainable consumption, problematic e-recycling processes, a fragile formal e-recycling sector, sustained and more harmful informal e-recycling practices, and more convoluted and unpredictable patterns of illegal e-waste trade. A close examination of the e-waste legacy contamination reveals critical human health concerns, including significant occupational exposure during both formal and informal e-recycling, and persistent environmental contamination, particularly in some developing countries. However, newly detected e-waste contaminants as well as unexpected sources and environmental fates of contaminants are among the emerging issues that raise concerns. Moreover, scientific knowledge gaps remain regarding the complexity and magnitude of the e-waste legacy contamination, specifically, a comprehensive characterization of e-waste contaminants, information on the scale of legacy contamination in developing countries and on the potential environmental damage in developed countries, and a stronger body of evidence of adverse health effects specifically ascribed to e-waste contaminants. However, the knowledge accumulated to date is sufficient to raise awareness and concern among all stakeholders. Potential solutions to curb e-waste issues should be addressed comprehensively, by focusing on two fronts: upstream and downstream. Potential upstream solutions should focus on more rational and eco-oriented consumer habits in order to decrease e-waste quantities while fostering ethical and sustained commitments from manufacturers, which include a limited usage of hazardous compounds and an optimal increase in e-waste recyclability. At the downstream level, solutions should include suitable and pragmatic actions to progressively reduce the illegal e-waste trade particularly through international cooperation and coordination, better enforcement of domestic laws, and monitoring in both exporting and receiving countries, along with the supervised integration of the informal sector into the recycling system of developing countries and global expansion of formal e-waste collection and recycling activities. Downstream solutions should also introduce stronger reverse logistics, together with upgraded, more affordable, and eco-friendly and worker-friendly e-recycling technologies to ensure that benefits are derived fully and safely from the great economic potential of e-waste.

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1. Introduction

Among other terms, electrical and electronic waste (e-waste), or waste electrical and electronic equipment (WEEE), are terms used to cover electrical and electronic equipment discarded as waste without intent of reuse (Step, 2014). E-waste offers particularly high potential for recovery as it contains valuable recyclable components such as gold, platinum and silver. However, e-waste also contains non-negligible amounts of potentially toxic substances (e.g., cadmium and lead) and is thus considered hazardous when improperly managed. These findings highlight the need for the safe and smart management (including proper recycling) and commercial exploitation of e-waste while preserving human health and environmental integrity, given the large volume of e-waste generated worldwide annually (41.8 million - metric tonnes (MMT) estimated in 2014) and its fast growth (Lundgren, 2012; Kiddee et al., 2013; Cucchiella et al., 2016; Step, 2016; Baldé et al., 2015). Canada, which generated an estimated 725,000 tonnes of e-waste in 2014, is well below the 2014 top five e-waste global generators, which were the United States (7.1 MMT), China (6.0 MMT), Japan (2.2 MMT), Germany (1.8 MMT) and India (I.7 MMT). However, with 20.4 kg of e-waste generated annually per inhabitant, Canada remains one of the highest contributors to e-waste volume in relative quantities in the Americas, right between the United States (22.1 kg/in.) and the Bahamas (19.1 kg/in.) (Baldé et al., 2015).

This review aims to expose the complexity of e-waste problems. Its objectives are (a) to provide a brief overview of the historical aspects of e-waste management; (b) to identify gaps, issues and challenges that greatly complicate e-waste management; (c) to gain insight into the current e-waste legacy contamination in terms of critical, emerging or still-unknown human health issues (including occupational health concerns) and environmental contamination, and (d) to propose solutions that could potentially curb e-waste issues both upstream and downstream.

2. Background: a bird's-eye view of the history of e-waste management

In the 1970s and 1980s, hazardous waste, including e-waste, was commonly shipped from industrialized countries to less developed nations in Asia, Africa, Central America and Eastern Europe (UNEP, 2010). The hazardous waste trade is rooted in the “Not in My Back Yard” syndrome in developed countries, an expression of the public's vehement stand against poor management of hazardous waste, including e-waste. Since the 1970s, it has led to the adoption of more stringent laws in the developed countries, such as The Resource Conservation and Recovery Act (RCRA) in the United States in 1976 (UNEP, 2010), which led to an escalation in the costs of hazardous waste disposal, while these costs remained low in less developed countries (Massari and Monzini, 2006; Andrews, 2009; UNEP, 2010).

E-waste trading led to heavy environmental contamination in receiving countries, where primitive recycling methods, incineration and landfilling of hazardous waste were widely practiced, supported by inadequate environmental awareness, controls and regulations (UNEP, 2010). To fight what was called the “toxic trade”, the Basel Convention on the Control of the Transboundary Movements of Hazardous Wastes and their Disposal was adopted in 1989 and came into force in 1992. The aim of this international treaty is to regulate the export of hazardous waste from industrialized countries (called “Annex VII countries” and composed of parties to the Basel Convention that are members of the Organization of the Economic Co-operation and Development (OECD) or the European Union (EU), as well as Liechtenstein) to less developed and vulnerable nations (called “non-Annex VII countries” and composed of all other parties to the Basel Convention). The fundamental purpose of the Basel Convention is to promote safe and sound hazardous waste management in order to safeguard human health and the environment. Its main objectives also include the limitation of hazardous waste generation and the restriction of hazardous waste exports unless the receiving country has confirmed the existence of environmentally sound practices for managing the imported waste (Andrews, 2009; Ahmad Khan, 2016).

Amendments to the Basel Convention, known as the Basel Ban or the Ban, were adopted in 1995 and 1997 to completely prohibit the export of hazardous wastes from Annex VII countries to non-Annex VII countries, while Annex VIII was added in 1998 to include e-waste. However, Annex IX, also added in 1998, still allows the export of certain categories of e-waste for strict reuse, for the purpose of giving the receiving parties access to the digital world through second-hand equipment (Basel Convention, 2011; Ahmad Khan, 2016).

A series of regulations and policies have since emerged worldwide at the regional, national and global levels to promote reuse and proper recycling, as well as a reduction in the use of toxic raw materials. For example, in 2003, the European Union adopted significant regulations such as the WEEE Directive, which sought to enhance e-waste collection, reuse and recycling, and the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive, requiring substitutions for or the limitation of certain toxic substances, including heavy metals and flame retardants (European Commission, 2017).

On a global scale, the Nairobi Declaration on the Environmentally Sound Management of Electrical and Electronic Waste was launched in 2006 (Lundgren, 2012). A multi-stakeholder partnership known as the Solving the E-waste Problem (StEP) Initiative, involving United Nations agencies as well as academic and governmental organizations, among others, was instituted in 2007 to achieve more sustainable e-waste management through an international information-sharing platform (Sthiannopkao and Wong, 2013). An entire battery of tools has also been developed and adopted over time in developed and some developing countries to support the safe and optimal handling of the e-waste stream: Extended Producer Responsibility (EPR), Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Multi-Criteria Analysis (MCA) (Kiddee et al., 2013).

Unfortunately, despite regulatory efforts and position papers, e-waste is still ill-managed, with the proper e-waste recycling (e-recycling) rate remaining extremely low worldwide, at roughly 15.5% of the global volume generated in 2014 (Baldé et al., 2015). Even more alarming is the fact that illegal shipments to more vulnerable countries continue to abound, as disclosed by a report of the Interpol Pollution Crime Working Group (Interpol, 2009).

Through a 2014–2016 investigation, a US environmental watchdog group called the Basel Action Network (BAN) unveiled the continuing traffic of e-waste from the US to developing countries (mostly China) and involving computer manufacturers, certified recycling companies and at least one major charity organization. More than 90% of e-waste was actually exported illegally under the guise of second-hand equipment (Hopson and Puckett, 2016). Following the BAN report, the US Environmental Protection Agency (US EPA) strongly condemned such illegal activities and levied a severe fine one of the US electronic recyclers involved (US EPA, 2016a; WDE, 2016).

Given the increasing volume of e-waste being generated worldwide, it is likely that illegal shipments to the developing world have been rising steadily since the Basel Convention, leading to a globalization of e-waste issues. About 50–80% of the e-waste generated in developed countries is considered to be illegally exported to low- and middle-income countries (Ghosh et al., 2016; Someya et al., 2016). China still receives the lion's share of all illegal e-waste, although countries such as the Philippines, India, Nigeria and Ghana remain attractive destinations. It is worth mentioning that most of the receiving countries have nonetheless ratified the Basel Convention and the Basel Ban (Rucevska et al., 2015; Hopson and Puckett, 2016; Terazono et al., 2017). It is estimated that between 1.5 and 2 MMT of e-waste are exported illegally to China from the European Union each year, despite the import ban imposed by China on all e-waste in 2000 (Huisman et al., 2015;

Geeraerts et al., 2016). Moreover, a recent survey conducted in Hong Kong revealed that some traders do not hesitate to "re-export" 90–100% of the used televisions shipped from Japan to China (Sugimura and Murakami, 2016).

Human health risks and environmental damage, particularly when related to unsafe e-waste handling and processing in developing countries, have therefore raised substantial concerns in the scientific community (Kiddee et al., 2013; Ahmad Khan, 2016). Through a systematic review, some authors have found what they consider to be plausible detrimental effects associated with exposure to e-waste contaminants. The vulnerable populations identified include not only workers, but also children and pregnant women living within or in the vicinity of unregulated recycling sites (Grant et al., 2013). E-waste has therefore become an emerging health risk for critically exposed populations in developing countries (Chen et al., 2011; Grant et al., 2013). This finding is attributed in particular to the relentless growth in e-waste and the ensuing and constantly reported environmental contamination with persistent and bioaccumulative organic pollutants, including flame retardants (Song and Li, 2015; Awasthi et al., 2016). Occupational health and safety issues related to both the proper recycling sector and unregulated e-waste activities are now subjected to greater scientific scrutiny. However, many aspects of the potential occupational exposure remain unknown (Ceballos and Dong, 2016; Tue et al., 2016a).

3. Ongoing gaps, issues and challenges in e-waste management

For e-waste management to be respectful of the environment and human health, it has to be properly and effectively handled. Effective e-waste management first consists of collecting and sorting e-waste, and repairing and reusing it whenever possible. End-of-life e-waste is then processed to remove and decontaminate all potentially toxic compounds, to properly recover valuable materials, and finally, to safely dispose of toxic parts and non-recyclable residuals (Namias, 2013; Baldé et al., 2015; Step, 2016). Unfortunately, e-waste management is currently facing significant, varied and complex gaps, issues and challenges that are often intertwined and that make e-waste problems so arduous to resolve.

One of the most critical gaps is the absence of a consistent definition of e-waste, which makes it even harder to precisely assess the massive volume generated worldwide and the dynamics of the current illegal e-waste trade, which in turn rank among the main e-waste issues (Lepawsky, 2015; Ahmad Khan, 2016). The evolving nature of e-waste, attributed among other things to technological progress, challenges the creation of a harmonized and definitive list of end-of-life electrical and electronic products (Ahmad Khan, 2016; Magalini, 2016). Hence, the WEEE Directive was amended in 2012 to include photovoltaic panels (European Commission, 2017).

The relentless manufacture of new electrical and electronic products (referred to as e-products in this paper) and the continuous growth of e-waste volume is also in itself a considerable issue. With an estimated annual growth rate of 4–5%, a global production of close to 50 MMT is predicted for 2018 (Baldé et al., 2015), which is plausible given that > 56 MMT of e-products came on the market in 2012 (Honda et al., 2016). For China alone, Xianli Zeng et al. (2016) suggested an annual growth of 25.7%, which could generate 15.5 MMT of e-waste in 2020, and almost double in 2030. This continuous growth is mainly fueled by planned obsolescence, which refers to the continuing decrease in the lifetime of e-products as a result of rapid technological updates, coupled with a drastic reduction in retail prices and strongly backed by marketing and advertising. E-products are quickly perceived as outdated, and undergo premature equipment failure (Pickren, 2015; Echegaray, 2016; Lebel, 2016; Zeng et al., 2017). This is particularly so for small electronic devices such as personal computers (PC), whose lifespan shortened from 4 to 6 years in 1997 to two years in 2005 (Lundgren, 2012), and cellular phones, whose lifespan collapsed in the United States from approximately 30 months in 1995 to < 20 months in 2005 (Ryneal, 2016).

More often than not, defective or damaged e-products tend to be replaced rather than repaired, further weakening e-products recovery and repair sector. This is partly due to limited public interest, technological obsolescence resulting in the unavailability of spare parts, unsuitable tools, the predominance of self-learning among repairers, time-consuming tasks during the repair process, high labour costs, and lack of strong initiative and effective logistics for testing and repairing defective items (Echegaray, 2016; Sabbaghi et al., 2017). The very design of e-products discourages their repair as their components are hastily assembled and securely attached (e.g., glued, bolted or soldered), thus making repair extremely difficult and time-consuming, if possible at all (Lundgren, 2012; Pickren, 2015; Sabbaghi et al., 2017). Obsolescence of e-products can, however, also be subjective or psychological, leading to unsustainable consumption of e-products. Echegaray (2016) defined subjective obsolescence as a consequence of "*the subjective devaluation of product perception based on learned experience, emotional attachments or benefits, status achievement, fashion, or esthetic quality*". The author found that consumers adopt throwaway practices with ease, replacing e-products because of new technology appeal, aesthetics or changing fashions, rather than declining performances or technical failure. This frenetic consumerism may also be stimulated by a growth in buying power, as shown by Kumar et al. (2017), who identified a positive correlation between the Gross Domestic Product (GDP) and e-waste generation in any country in the world, regardless of the number of inhabitants.

Not only are we witnessing the growth of e-waste volume, but the process of calculating global e-waste volume is also facing challenges due to the aforementioned absence of a clear e-waste definition, the extreme scarcity and inefficient collection of official data, the scanty data on both legal and illegal e-waste trans-boundaries and the lack of awareness among stakeholders (Honda et al., 2016; Morris and Metternicht, 2016; Petridis et al., 2016; Tran et al., 2016; Kumar et al., 2017). These data remain fundamental for receiving countries, as e-waste volume is generated not only by locally purchased e-products but also by imported second-hand equipment (referred to as the "*invisible inflow*").

The dearth of reliable data, combined with an increased e-waste volume, give rise to unpredictable and convoluted patterns of illegal e-waste trade. Geographies and the dynamics of e-waste trafficking have turned it into a more complex web. For instance, despite the official ban on e-waste imports, several Asian countries exchange e-waste among themselves, and some countries such as Ghana and Nigeria are still the main receivers of exports not only from Israel, Belgium, the United States and Canada but also from Singapore and India (Lepawsky, 2015; Lines et al., 2016; Someya et al., 2016). This may in part be attributed to some gaps, limitations and contradictions that can be pinpointed in the Basel Convention. Notably, the coming into force of the Basel Ban has still been delayed, as only 89 countries have ratified it so far (Basel Convention, 2017) while 90 ratifications are required (Ahmad Khan, 2016). Major e-waste producing countries like the United States have not yet ratified the Basel Convention itself, although the US was among the first signatories (Bradford, 2011; Ahmad Khan, 2016). In addition, by allowing e-waste exportation for strict reuse, Annex IX has provided fertile ground for the illegal trade through re-categorization of non-functional or nearly-out-of-date e-waste. False custom declarations are known to be common, disguising hazardous e-waste as used e-products for the second-hand market, plastic or metal scrap (Ahmad Khan, 2016; Geeraerts et al., 2016; Milovantseva and Fitzpatrick, 2016). There are also certain gaps in the customs rules of several countries, including a shortage of international information sharing, human resources, training and logistics to check each container received and to distinguish between still-functional goods and actual waste. Moreover, hazardous waste, non-hazardous waste and non-waste (used and new goods) often have identical six-digit-codes in the Harmonized

Commodity Description and Coding System (HS) used by customs services across the globe (Ahmad Khan, 2016; Huisman et al., 2015; Geeraerts et al., 2016; Grant and Oteng-Abadio, 2016).

Another pivotal issue in e-waste management is the inherent difficulties of the e-recycling processes. Despite some significant improvements, metal recovery technologies are still underperforming (e.g., difficulties in recycling single valuable metals), immature and/or polluting (Zhang and Xu, 2016). Some e-waste components such as printed circuit boards, CRT monitors and LCD screens also remain extremely hard to recycle, mainly due to their complexity, their hazardous nature and inefficient recycling technologies, so much so that many recyclers simply refuse to process them (Edwards, 2016; Singh et al., 2016). The same can be seen with e-products of a more compact design, for which recycling calls for state-of-the-art, costly, and labour- and energy-intensive processes to safely segregate and optimally recover materials. However, few facilities are equipped with the technical know-how required to end-process e-waste (Lundgren, 2012; Duan et al., 2016; D'Adamo et al., 2016; Zhang and Xu, 2016; Tansel, 2017).

Perhaps the most important problem in terms of e-waste's impact on the environment and human health is the fact that numerous e-waste products still contain hazardous components that have already been banned or restricted in several countries. These include heavy metals, ozone-depleting substances and persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) and brominated flame retardants (Baldé et al., 2015; Xiaobo Zheng et al., 2016; Matsukami et al., 2017). Thus, the global e-waste generated in 2014 was estimated to contain 2.2 MMT of leaded glass, 0.3 MMT of lead/lithium/cadmium/mercury-based batteries and 4000 tons of ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) (Baldé et al., 2015).

There have been efforts to replace potentially toxic substances in the manufacturing process of e-products. For instance, flat screen monitors with liquid crystal displays (LCDs) have replaced leaded-glass CRT monitors. However, their recycling is also hazardous due to the presence of toxic chemicals such as Hg, As, Cr and Ba (US EPA, 2016b; Woo et al., 2016; Tansel, 2017). A similar issue is observed with the substitution of certain chemicals in the manufacturing process, such as the replacement of PBDEs by halogen-free organophosphorus flame retardants, where the substitute is unfortunately proving to be more persistent than predicted (Gramatica et al., 2016). Regrettably, the promising development of green electronics processes, such as the inclusion of biodegradable electronic components (e.g., cellulose-based printed circuit boards), which would reduce the toxic potential of e-waste, is still fairly slow (Guna et al., 2016; Ma et al., 2016). Additionally, there are limitations in the information provided about the chemicals included in e-products, making the proper disposal of toxic waste even more challenging. Indeed, the publicly available and/or relevant data for recyclers is scarce, and there is deficient chemical composition data disclosure among stakeholders involved in the e-product chain (e.g., chemical and formulation manufacturers, brand-name owners, recyclers) (Scruggs et al., 2016; US EPA, 2016b; Woo et al., 2016).

Finally, the e-waste recycling industry often employs individuals from socially marginalized or vulnerable groups such as temporary workers, immigrants or prisoners (Ceballos and Dong, 2016). In developing countries, it is not uncommon to find children working in e-recycling (Robinson, 2009). For example, in Guiyu, China, e-waste workers tend to be internal migrants, many of whom are minors (Sthiannopkao and Wong, 2013). An evaluation of an electronic scrap recycling facility in the United States found that roughly half of all employees were immigrants (Page et al., 2015). Similarly, the United States Department of Justice (2010) investigated safety concerns of an electronic waste recycling program among inmates in federal prisons in the United States. Workers from marginalized social groups frequently have less economic security, and their vulnerable social position often contributes additional barriers to safety and health at work, which leads to an increased risk of occupational injury and illness and exacerbates the safety challenges faced by the e-waste industry (Krieger, 2010; Flynn, 2014).

All of the interconnected gaps, issues and challenges mentioned here render the formal e-recycling sector[1] more fragile. While most e-waste is handled in an informal manner in developing countries (Gu et al., 2016), formal e-recycling rates of the total e-waste remain very low in developed countries: 35% in the European Union in 2012 (Huisman et al., 2015), 29% in the United States in 2012 (Seeberger et al., 2016) and around 24 to 30% in Japan, 12% in Canada and roughly 1% in Australia, for all e-waste generated in 2014 (Baldé et al., 2015). Formal e-recycling is usually seen as unprofitable due to the need for high investment, dependency on governmental subsidies and elevated labour costs, all of which are outweighed by underperforming material recovery and low profits (Lundgren, 2012; Ryneal, 2016). There is also a lack of regulation, as well as challenging certification programs, limited implementation of various WEEE directives, and a great need of federal government involvement in compliance measures and financial support (Mohanty et al., 2015; Edwards, 2016; Morris and Metternicht, 2016). In addition, many deficiencies remain in official collection systems in developed countries, in part because of the lack of collection points, the financial costs associated with recycling and transportation, and even stealing activities (e.g., illegal traffic in e-waste) (Huisman et al., 2015; Li et al., 2015; McCann and Wittmann, 2015; Wilson et al., 2017). In addition, massive e-waste quantities and fast growth place a particular burden on collection logistics and proper e-recycling infrastructures (Tansel, 2017). In developing countries, informal collection systems are in most cases well-organized, offering more convenient door-to-door services at better prices than offered by formal collectors (Chi et al., 2014; Gu et al., 2016; Borthakur and Govind, 2017). The sustainability of informal e-recycling activities in developing countries can be explained by the fact that they provide a convenient livelihood system through the business and job opportunities they create, thus improving the quality of life of vulnerable populations (Ahmad Khan, 2016; Ardi and Leisten, 2016; Grant and Oteng-Abadio, 2016). Despite government initiatives, the implementation of a formal e-recycling sector in developing countries faces many barriers, such as high costs and supply deficiency, as well as the lack of strict regulation, a clear legal framework, adequate infrastructure, specific training, risk awareness and financial incentives (McCann and Wittmann, 2015; Geeraerts et al., 2016; Gu et al., 2016).

Finally, another crucial issue lies in the inconsistency of public awareness and willingness regarding proper e-recycling practices. Level of awareness varies from a complete lack among consumers in some developing countries (Liang and Sharp, 2016; Nartey, 2016) to favourable attitudes towards, but marginally adequate behaviour regarding, formal e-recycling in both developed and developing countries (Borthakur and Govind, 2017; Echegaray and Hansstein, 2017).

4. E-waste legacy contamination

E-waste handling and processing have the potential to release a complex blend of contaminants in various environmental matrices. These releases can be more or less significant, depending on the processes used and the protective measures implemented. Contaminants in e-waste are released in highly heterogeneous mixtures, whose composition varies according to e-waste types and age, as well as handling and

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[1] Formal e-waste recycling refers to activities carried out in facilities that are usually licensed and/or under the control of some legal authority and that comply with environmental laws and regulations (Fujimori et al., 2012; McCann and Wittmann, 2015; Ceballos and Dong, 2016). By contrast, informal e-recycling is generally considered less appropriate as it is scantily regulated, is potentially more harmful, has a very limited investment capacity for final disposal and usually takes place in small-scale and scattered workshops or domestic backyards (McCann and Wittmann, 2015; Ceballos and Dong, 2016; Tao et al., 2016; Terazono et al., 2017).

Table 1
Major e-waste primary contaminants.
Based on information provided by Cummings et al. (2012), Lundgren (2012), Kiddee et al. (2013), Fornalczyk et al. (2013), Klaassen (2013), Namias (2013), Haque et al. (2014), Julander et al. (2014), Szałatkiewicz (2014), Baldé et al. (2015), Bellanger et al. (2015), Cucchiella et al. (2015, 2016), Son et al. (2015), US EPA (2015), Zheng et al. (2015), Cayumil et al. (2016), Gramatica et al. (2016), Matsukami et al. (2016, 2017), Nartey (2016), Someya et al. (2016), Woo et al. (2016), American Chemistry Council (2017), ATSDR (2017), Aschberger et al. (2017), IARC (2017), Tansel (2017), and Toxnet (n.d.).

Contaminants	Example of sources	Main types of toxicity
Metals		
Aluminum	WPCBs, microchips, hard drives, LED monitors, plastic housing; plastics, cables and wires containing inorganic flame retardants (e.g. aluminum hydroxide and trihydroxide)	Lung irritant, neurotoxic
Americium 241	Ionization smoke detectors	Carcinogenic, in the case of high dose radiation
Antimony	Tin-lead alloys, WPCBs, CRT; LCD TVs; plastics, cables and wires containing inorganic flame retardants (e.g. antimony trioxide[a])	Lung, eye and gastro-intestinal irritant
Arsenic	Dopant for semi-conductors, PTVs, LCD monitors and TVs	Carcinogenic, hematotoxic, endocrine disrupter
Barium	CRT, fluorescent lamps, LCD TVs, PTVs, gutters in vacuum tubes.	Neurotoxic, cardiotoxic, gastro-intestinal irritant
Beryllium	WPCBs, power supply boxes, ceramic components	Berylliosis, carcinogenic
Cadmium	Batteries, toners, cartridges, plastics, WPCBs, solder, chip resistors, CRT, PTVs, cell phones, infrared detectors	Carcinogenic, cardiotoxic, nephrotoxic, endocrine disrupter
Cobalt	Batteries, hard drives, laptop computers, LCD monitors and TVs, PTVs, CRT	Cardiotoxic, allergen (asthma), possibly carcinogenic to human (IARC)
Copper	Cables, electrical wiring, WPCBs, microprocessors, terminal strips, plugs, PTVs, cell phones	Lung, eye and gastro-intestinal irritant
Gallium	Data tapes, integrated circuits	Skin and probably eye and mucous membrane irritant
Hexavalent chromium VI	Corrosion resistant coatings, WPCBs, data tapes, floppy disks, pigments, PTVs	Carcinogenic (lung cancer), sensitizer, skin irritant
Indium	LCD TVs, transistors, rectifiers	Probably carcinogenic to human (IARC[b]), eye and lung irritant, indium lung disease
Lead	CRT (glass, solder), LCD TVs, PTVs, fluorescent tubes, WPCBs, lead-acid batteries	Probably carcinogenic to human (IARC[b]), neurotoxic, cardiotoxic, nephrotoxic, endocrine disrupter
Lithium	Rechargeable batteries	Skin and eye irritant
Manganese	Cell phones, CRT, PCBs	Cardiotoxic, neurotoxic, lung irritant, endocrine disrupter[c]
Mercury	Fluorescent tubes, compact fluorescent lamps, batteries, switches, thermostats, sensors, monitors, LCD TVs, laptop computers	Neurotoxic, skin, eye and gastro-intestinal irritant, endocrine disrupter
Nickel	Nickel-cadmium batteries, ceramic components of electronics, computers, LCD monitors and TVs, laptop computers	Carcinogenic, sensitizer
Platinum	WPCBs, LCD and LED notebooks, cell phones	Eye and lung irritant
Selenium	Rectifiers, WPCBs, old photocopiers	Eye, skin and lung irritant, selenosis at high concentrations
Silver	PTVs, laptop computers, LCD and LED monitors	Nephrotoxic, reprotoxic
Thallium	Semi-conductors, batteries	Neurotoxic, cardiotoxic, hepatotoxic, birth defects
Tin	LCD screens, tin-lead alloys, LED monitors	Skin and eye irritant, hematotoxic, hepatotoxic
Tungsten	LCD and LED monitors	Lung, eye and skin irritant
Vanadium	PCBs, red phosphor emitters, tablet PCs	Cardiotoxic, nephrotoxic, skin and lung irritant
Yttrium	LCDs, superconductors, lasers	Lung and eye irritant
Zinc	WPCBs, PTVs, CRTs, batteries, soldering flux, cell phones, plastics, wire and cables containing inorganic flame retardants (e.g., in the form of zinc stannate)	Neurotoxic, hematotoxic, gastric irritant, may induce fume fever (inhalation of large amount of zinc in fume or dusts), probably endocrine disrupter[d]
Organic pollutants		
Halogenated flame retardants – Brominated flame retardants (e.g., PBDEs, TBBPA, HBCD) – Novel brominated flame retardants (e.g., DBDPE, TBPH, TBBPA-BGE) – Chlorinated flame retardants (e.g., DPs, DBHCTD)	WPCBs, plastics Condensers, transformers, plastics	Endocrine disrupter, neurotoxic, carcinogenic (chlorinated flame retardants)
Halogen-free flame retardants Organophosphorus-based flame retardants[e] (e.g., TCEP, TCIPP, TDCIPP, TPHP/TPP, BPA-BDPP, PBDPP, and DOPO) Nitrogen-based flame retardants[f] (e.g., melamine cyanurate, melamine polyphosphate)	IT housing, plastics, epoxy resins in WPCBs	**Organophosphorus:** endocrine disrupter **Nitrogen-based**: nephrotoxic, neurotoxic
PCBs	Old capacitors and transformers, fluorescent lamps, electrical motors	Endocrine disrupter, hepatotoxic, carcinogenic
Ozone-depleting substances		
e.g., CFCs, HCFC, HFC, HCs	Old refrigerators, freezers and air conditioning units, insulation foam	Neurotoxic, lung and eye irritants
Other components		
Phthalates	Plasticizers to soften plastics and rubber	Endocrine disrupter, reprotoxic, hepatotoxic
PFOS/F	Antireflective coating	May effect lipid metabolism (increase in blood cholesterol level)

(*continued on next page*)

Table 1 (*continued*)

Contaminants	Example of sources	Main types of toxicity
PVC	Wiring and computer housing	Related to toxicity of dioxins and furans generated during PVC burning (see Table 2)

Legend: BPA-BDPP, bisphenol A bis(diphenyl phosphate); CFCs, chlorofluorocarbons; DBDPE, decabromodiphenyl ethane or 1,2-bis(pentabromodiphenyl)ethane; DBHCTD; dibromohexachlorotricyclotridecene; DPs, dechlorane plus; DOPO, 9,10-dihydro-9-oxa-10-phospaphenanthrene-10-oxide; HBCD, hexabromocyclododecane; HC, hydrocarbons; HCFC, hydrochlorofluorocarbons; HFC, hydrofluorocarbons; PBDPP, 1,3-phenylene bis(diphenyl phosphate) or resorcinol bis(diphenyl phosphate); PCBs, polychlorinated biphenyls; PFOS/F, perfluorooctane sulfonate; PVC, polyvinyl chloride; TBBPA, tetrabromobisphenol A; TBBPA-BGE, tetrabromobisphenol A-bis bis(glycidyl)ether; TBPH, bis(2-ethylhexyl)-3,4,5,6-tetrabromophthalate; TCEP, tris(2-chloroethyl) phosphate; TCIPP, tris(2-chloroisopropyl) phosphate; TDCIPP, tris(1,3-dichloroisopropyl) phosphate; TPHP/TPP, triphenyl phosphate.

CRTs, cathode ray tubes; IT, information technology; LCDs, liquid crystal displays; LED, light-emitting diode; PTVs, plasma televisions; PCs, personal computers; TVs, televisions; WPCBs, waste printed circuit boards.

[a] Often associated with other halogenated and non-halogenated flame retardants (Aschberger et al., 2017).

[b] According to the International Agency for Research on Cancer (IARC) classification.

[c] Alteration of the production and secretion of sexual hormones in rats in some animal studies (ATSDR, 2017).

[d] Infertility in rats in some animal studies (ATSDR, 2017).

[e] There are also inorganic phosphorus-based flame retardants such as red-phosphorus and phosphates (Aschberger et al., 2017).

[f] Often associated with phosphorus-based flame retardants (US EPA, 2015).

processing. The physical state of the released contaminants varies with the nature of the handling process, and includes particulate matter, gas, vapours, aerosols, solid residues left after a smelting or leaching process, liquids (spent acid or waste water) or semi-liquids (sludge from leaching solutions). Three large categories of contaminants may be discharged (Schluep et al., 2009; Lundgren, 2012; Cayumil et al., 2016):

- different classes of primary contaminants, which are mostly metals and persistent and bioaccumulative organic substances used as part of e-waste composition (Table 1), generally during pre-processing activities (e.g., manual dismantling, shredding, and crushing), end-processing activities (e.g., open burning of e-waste or pyrometallurgical/hydrometallurgical routes for extracting precious materials), and incineration of e-waste (both integral and residual), and landfill leachates;
- secondary contaminants, which are mostly persistent and bioaccumulative organic substances (Table 2) that derive from the combustion of primary contaminants such as PCBs or other ingredients (e.g., polyvinyl chloride/PVC in plastic or cabling), or during e-waste open burning, smelting or incinerating operations;
- tertiary contaminants, which are mostly acids and cyanides (Table 2), emitted by chemicals such as the acids and cyanides used in material recovery processes.

Human exposure to e-waste contaminants may be occupational or environmental, affecting both workers and the general population. As mentioned before, informal e-recycling sectors may involve not only adult workers but also children, teenagers and older adults, who are mainly involved in outdoor activities, including dismantling and open burning. While most formal e-recycling facilities show a particular concern for worker protection and are more able to invest in safe practices and disposal, workers involved in informal e-recycling activities are generally untrained and not equipped with personal protective equipment. They tend to use risky practices and sometimes work in unsafe conditions with no efforts to protect themselves, mainly due to the lack of knowledge of or access to protective measures (Iqbal et al., 2015; Adesokan et al., 2016; Amankwah-Amoah, 2016; Ceballos and Dong, 2016; Terazono et al., 2017).

Exposure may also occur through pollutants persisting in different environmental matrices such as air, surface water and groundwater, soil, sediment, food and wastewater. Workers involved in the informal sector may face additional exposure to those contaminants as a result of take-home exposures or environmental contamination, as they usually live within close vicinity of or even within recycling sites. Exposure pathways are multiple, depending not only on the nature of the e-waste processing, but also on the type of contaminants involved. They may include inhalation, ingestion, dermal contact, and transplacental or lactational routes (Lundgren, 2012; Grant et al., 2013; Kiddee et al., 2013; Iqbal et al., 2015; Asampong et al., 2015; Carlson, 2016).

As is the case with other toxic waste, environmental damage from a lengthy history of inadequate e-waste management is expected to linger for a long time after the closure or upgrading of e-waste recycling sites further to the implementation of tighter environmental regulations or a shift from informal practices to more regulated ones (Xinjin Xu et al., 2015; Ceballos and Dong, 2016; Yan Wang et al., 2016). This is reflected in the e-waste legacy contamination, which is even more critical given the sustained involvement of persistent and bioaccumulative organic pollutants. According to Lebel (2016), exposure to e-waste contaminants may "*defy the temporal practices and qualities associated with traditional waste management strategies*".

4.1. E-waste legacy contamination and human body burden

The environmental burden associated with e-waste contaminants began receiving attention from environmental advocacy groups in the 1990s (Ahmad Khan, 2016). A 2002 report from two non-governmental organizations (NGOs)–the Basel Action Network and the Silicon Valley Toxics Coalition (SVTC)–described some particularly harmful e-recycling activities (e.g., open-pit acid baths, smelting operations on the ground, crushing and open dumping of CRT TVs along rivers, open burning of wires within cities and near rivers and streams) with the complete absence of personal protective measures in Guiyu (China), Sher Shah (Pakistan) and New Delhi (India). Water sampled from rivers adjacent to WPBCs burning sites in Guiyu revealed lead concentrations 190 times higher than those set in the World Health Organization (WHO) Drinking Water Guidelines in 2001. Sediments sampled from the same location showed barium, tin and chromium concentrations respectively 10, 152, and 1338 times higher than the US EPA threshold for environmental risk in soil (BAN/SVTC, 2002).

Despite regulatory efforts and technological progress over the years, studies continue to uncover human exposure and environmental contamination attributable to e-waste handling and recycling activities, especially in developing countries (Lundgren, 2012; Song et al., 2015; Du et al., 2016; Awasthi et al., 2016). Table 1, in the Appendix A, presents some of the most recent field studies (including a few human risk assessments) that have documented environmental impacts attributable to e-recycling practices. The targeted contaminants were mainly heavy metals and POPs (flame retardants, PCBs, PAHs). Children constitute the population most sensitive to e-waste exposure as they are likely to receive high doses of contaminants, in particular because of their exposure through multiple routes (e.g., breastfeeding, placental, dermal, hand-to-mouth, object-to-mouth, take-home

Table 2
Some secondary and tertiary e-waste contaminants released during e-waste processing.
Based on information provided by Schluep et al. (2009), Lundgren (2012), Grant et al. (2013), Kiddee et al. (2013), An et al. (2014), Cayumil et al. (2016), J. Chen et al. (2016), Zhang et al. (2016), Aschberger et al. (2017), ATSDR (2017), Iannicelli-Zubiani et al. (2017), IARC (2017), and Toxnet (n.d.).

E-waste processing	Most common contaminants emitted	Category of contaminants, examples of source or use	Main types of toxicity
Combustion of e-waste containing PCBs, plastics and PVC in order to recover precious materials (open burning activities, pyrometallurgical process in a furnace) Incineration of e-waste residues as disposal strategy	PAHs (e.g., phenanthrene, anthracene, fluoranthene, benzo[*a*]pyrene, benz[*a*] anthreacene)	Secondary (from brominated, chlorinated and organophosphorus FRs in plastics and from PVC)	Carcinogenic[a], photosensitizer
	PCDD/Fs PBDD/Fs PXDD/Fs		Immunotoxic, carcinogenic, reprotoxic, endocrine disrupters, may induce birth defects and also dermal damage (chloracne)
	Bisphenol A	Secondary (from combustion of polycarbonate plastics)	Endocrine disrupter
	Gases such as carbon monoxide and methane	Secondary (generated during smelting process)	Asphyxia
	Acids	Secondary (e.g., hydrobromic acid from brominated FRs, hydrochloric acid from chlorinated FRs and from incomplete combustion of PVC; phosphoric acid from organophosphorus FRs)	Induce from mild to severe burns to eyes and skin, sore throat, respiratory problems, corrosive injuries to lips, mouth, throat, etc., if swallowed
Pyrometallurgy for metal refining	Acids (e.g., hydrochloric, nitric, sulphuric)	Tertiary (used as electrolyte solutions for electro-refining)	Induce from mild to severe burns to eyes and skin, sore throat, respiratory problems, corrosive injuries to lips, mouth, throat, etc., if swallowed
Hydrometallurgy for metal refining	Acids (e.g., hydrochloric, nitric, sulphuric)	Tertiary (used as leaching agents, for solvent-extraction and for electroextraction solutions)	Induce from mild to severe burns to eyes and skin, sore throat, respiratory problems, corrosive injuries to lips, mouth, throat, etc., if swallowed
	Cyanides	Tertiary (used as reagents)	Neurotoxic, cardiotoxic, may induce chest pain, breathing difficulties, increase in size of thyroid gland
	Thiourea	Tertiary (used as reagents)	Photosensitizer, hematotoxic

Legend: FRs, flame retardants; PBDD/Fs, polybrominated dibenzo-*p*-dioxins and dibenzofurans; PAHs, polycyclic aromatic hydrocarbons; PCBs, polychlorinated biphenyls; PCDD/Fs, polychlorinated dibenzo-*p*-dioxins and dibenzofurans; PVC, polyvinyl chloride; PXDD/Fs, mixed polybromochloro-dibenzo-*p*-dioxins and dibenzofurans.

[a] Some PAHs are *probably carcinogenic to humans* (e.g., ben[*a*]anthracene and benzo[*a*]pyrene), while some are *possibly carcinogenic to humans* (e.g., benzo[*a*]fluoranthene and benzo[*k*] fluoranthene), according to the IARC classification (ATSDR, 2017).

exposure), their higher basal metabolism than adults, their larger surface area in relation to body weight and their lower toxin elimination rates (Xiang Zeng et al., 2016).

Several studies have explored the body burden resulting from e-waste exposure, not only in formal and informal workers but also in the surrounding population. A literature review by Ceballos and Dong (2016) reported that, despite the use of advanced technologies, workers' exposure to some toxic metals in formal e-recycling facilities exceeds the occupational exposure limits, while biological levels of flame retardants were found to be higher than those of unexposed reference groups. These authors suggested that engineering and administrative controls can lower occupational exposure, which means that protective measures implemented thus far in some licensed facilities have failed to create a completely safe work environment. Investigating occupational exposure in CRT recycling facilities in France, Lecler et al. (2015) identified a few highly polluting steps (e.g., CRT decontamination) and concluded that there is a need for general ventilation, better occupational risk management and medical biomonitoring. High exposure to heavy metals, furans, dioxins, PCBs and other POPs were mostly reported for workers in the informal sectors and the surrounding population (Song et al., 2015; Cayumil et al., 2016; Edwards, 2016; Li et al., 2017). Table 2, in the Appendix A, reports on recent studies that have carried out personal air and/or biological sampling to investigate the body burden of e-waste exposure in workers and surrounding populations.

However, ongoing investigations on e-waste legacy contamination are revealing emerging issues that also raise concerns, thus complicating the situation even further. Some of these are detailed in Table 3.

4.2. Remaining gaps in scientific knowledge of e-waste legacy contamination

Despite scientific interest in the e-waste legacy contamination, many knowledge gaps remain regarding its complexity and the scale of its potential environmental damage, but also in the identification of adverse health effects attributable to e-waste contaminants. Table 4 presents some important scientific knowledge gaps that still need to be bridged for a better assessment of the human and environmental burdens of e-waste management. The most significant gap is probably the lack of direct evidence of causal relationships between exposure to e-waste contaminants and adverse health effects, in part due to inconsistencies in epidemiological data, absence of dose-response relations and still-poor documentation of biological mechanisms of the effects of e-waste contaminant mixtures (Grant et al., 2013; Xinjin Xu et al., 2015; Xiang Zeng et al., 2016).

5. Potential solutions to curb e-waste issues

Solving e-waste issues is a long-term, challenging and costly task and calls for the full collaboration of all stakeholders involved (e.g., government, scientific community, chemical manufacturers, e-product designers, retailers and collectors, e-recyclers and end consumers). However, any action taken to address e-waste problems could benefit from a firm governmental position in terms of tighter laws, regulations and policies, including surveillance of the Extended Producer Responsibility (EPR) system, awareness initiatives, sustained financial, technical, logistical, and training support, and even international co-operation. The aim should be to steadily increase the engagement and

Table 3
Emerging issues regarding the e-waste legacy contamination.

Emerging issues	Comments
Increased environmental and human burdens of a mix of typical and new persistent and bioaccumulative components, used as alternatives to PBDEs and/or plasticizers	Accumulations of new flame retardants (e.g., bisphenol A bis(diphenyl phosphate) [BPA-BDPP], dechlorane plus [DPs], (2-ethylhexyl)diphenyl phosphate [EHDPP], hexabromobenzene [HBB], tris(2-chloroethyl) phosphate [TCEP], tris(1,3-dichloro-2-propyl) phosphate [TDCIPP], decabromodiphenyl ethane [DBDPE], triphenyl phosphate [TPHP]) found in dust, soil, sediment and food in informal e-recycling areas in China (P. Wu et al., 2016; Xiaobo Zheng et al., 2016; He et al., 2017) and Vietnam (Someya et al., 2016; Matsukami et al., 2016, 2017; Tao et al., 2016). High concentrations of organophosphate metabolites, deriving from PBDE alternatives (TCEP, TDCIPP, TPHP) also found in urine of people living and/or working in informal e-recycling areas of Longtang town, China (Lu et al., 2017).
Environmental accumulation of emerging dioxin-related compounds	Accumulation of dioxin-like compounds in soil and sediment of informal e-recycling area in Vietnam. Toxic equivalent (TEQ) exceeding the Japan and Netherlands' criteria for human health (Suzuki et al., 2016). High levels of mixed halogenated (brominated and chlorinated) dibenzo-*p*-dioxins/dibenzofurans (PXDD/Fs) also found in soil of burning site in Agbogbloshie, Ghana (Tue et al., 2016b).
Release of potentially toxic volatile organic compounds (VOCs) during e-waste combustion	Waste printed circuit boards (WPCBs) and plastic casings' burning release high concentrations of VOCs, heavy metals and POPs. Aromatic hydrocarbons (AHs) (e.g., benzene, toluene, ethyltoluene, and phenol) identified as the dominant group of emitted VOCs, implying both non-cancer and cancer risk for workers, especially when using rotary incinerators. Predominance of AHs due to bisphenol A in the epoxy formulation in WPCBs (An et al., 2014; J. Chen et al., 2016). Combustion of WPCBs releases a complex mixture of AHs and aromatic amine hydrocarbons, including aniline (Sahle-Demessie et al., 2016).
Migratory effect and pollution scale	Potentially high environmental migratory abilities of alternative flame retardants (particularly DPs and oligomeric organophosphorus [o-PFRs]) and their breakdown products, resulting in weathering processes during e-waste open storage and burning (Matsukami et al., 2017). Higher scale of pollution by organic pollutants (e.g., halogenated flame retardants, dioxin-like compounds, polyaromatic hydrocarbons [PAHs]) estimated, compared to metals, which may increase contamination risks for adjacent and surrounding areas and increase human health risk impacts (Fujimori and Takigami, 2014; Xiao et al., 2016; Terazono et al., 2017; Yuan et al., 2017). Outflow of PAHs from e-recycling activities in Guiyu (when facilities were in operation) may affect local population and also population living up to 30 km downstream in coastal region of Haimen Harbour (Shi et al., 2016).
Other significant contributors to environmental burden	**Abandoned e-recycling sites** Environmental persistence and potential dissemination of e-waste contaminants from abandoned e-recycling sites remain a human health risk years after closure of these sites. Abandoned burning sites in China remain a source of polychlorinated biphenyls (PCBs), especially during warmer seasons (Yan Wang et al., 2016, 2017). Heavy metals found to accumulate in ponds after being transported by rainfall from contaminated surface soil of abandoned e-recycling areas, thus posing a serious human health risk via dietary intake of agricultural products (Wu et al., 2015). **Formal e-recycling sector** Soil contaminated with heavy metals, PCBs, brominated flame retardants and dioxin-related compounds (DRCs) within and around an e-recycling compound in the southeastern part of Tianjin City (Zhao et al., 2013; Hong et al., 2016). Same results reported for an emerging large-scale complex in Taizhou (Ma et al., 2008, 2009). Several officially licensed facilities, which are engaged in low-tech e-recycling practices, are still carrying out rudimentary activities such as open burning of wires and cables (Ma et al., 2008, 2009; Hong et al., 2016). There have been instances of formal facilities in the US involved in legal litigation for leaving contaminated sites after bankruptcy or for illegally dumping e-waste on abandoned lots (Elliot, 2016).
Other influencing factors to consider in human health risk assessment	Migrant e-recycling workers in Taizhou, China, had PCB-related health risk 3.8 times greater than that of local residents, both for cancer and non-cancer risks. Suggestion made that non-dietary exposure (e.g., lifestyle and economic status) should also be considered in human health risk assessment among workers (Yalin Wang et al., 2016). In Agbogbloshie, Ghana, lower exposure to PCBs found for e-recycling workers. Low living standard, associated with less fish consumption, the major dietary source of PCB exposure (Wittsiepe et al., 2015).
Other critical exposure routes	Dermal uptake from e-waste airborne contaminants (skin absorption of particulates and gaseous organic contaminants from e-waste combustion fumes) considered a significant exposure route for e-recycling workers and populations living in and around recycling areas, especially for organic pollutants such as flame retardants and plasticizers with low molecular weights that allow high dermal penetration rates and large skin-air partition coefficients (C. Wu et al., 2016).

adhesion of other stakeholders (Gu et al., 2016; Heacock et al., 2016; Step, 2016; Z. Wang et al., 2016c; Zeng et al., 2017). That being said, the gaps have widened between rapidly evolving technological markets, high consumption of e-products and, hence, high generation of e-waste, on the one hand, and the resources available to deal adequately with the potentially hazardous e-waste flow, on the other. For instance, despite three decades of intense research, the performance and stability of substitute materials for e-product manufacturing are still problematic (Li et al., 2015). Yet, given the serious human health risks and environmental burden, it is imperative that the e-waste problem-solving process gain momentum. A comprehensive approach is suggested here that involves working on two fronts – at the upstream and downstream

Table 4
Some scientific knowledge gaps regarding the e-waste legacy contamination.

Knowledge gaps	Comments
Comprehensive characterization of e-waste contaminants including specific properties (e.g., toxicity, environmental behaviour, potential interaction between contaminants in the environment)	● Unidentified halogenated PAHs are released during e-waste combustion. Their potential toxicity is still unknown to date (Tue et al., 2016a). ● Speciation and leaching behaviour of metals in e-waste contaminated areas have been little studied (Cui et al., 2017). ● More studies are needed to assess trophic transfer of hexabromocyclododecanes (HBCD) in the food webs (Zhu et al., 2017). ● There are still uncertainties about alternative flame retardants with regard to their environmental behaviour, potential toxicity, metabolism, persistence and potential of bioaccumulation in biota (Matsukami et al., 2016, 2017; Tao et al., 2016; Zhu et al., 2017). ● The interplay between contaminants is still poorly documented; however, Pb, Cu, Zn, and Br contained in contaminated soil and ash mixture of open e-waste burning areas in Agbogbloshie, Ghana, are thought to influence the formation of dioxin-related compounds (Fujimori et al., 2016).
Characterization of human exposure to alternative flame retardants	● More studies are needed to investigate human exposure to alternative flame retardants and assess their human health risk (Matsukami et al., 2017). Levels of some novel brominated flame retardants in samples of foodstuffs exceeded those in foods from control sites in informal e-recycling area in Taizhou City, Eastern China (Labunska et al., 2015).
Human health exposure and risk assessment related to multiple exposure from e-recycling	● Human health risks related to multiple exposure in developing countries, for workers and surrounding populations, are still poorly documented (Grant et al., 2013; Ceballos and Dong, 2016; L. Xu et al., 2016; Xiang Zeng et al., 2016; Akortia et al., 2017). Despite enduring exposure of Ghanaian e-recycling workers to the highest levels of chlorinated and brominated dioxin-like compounds ever reported, cancer risks related to complex mixtures of potential mutagenic PAHs and derivatives are also still poorly assessed (Tue et al., 2016a). ● Data and awareness on take-home exposure are still lacking (Perkins et al., 2014; Ceballos and Dong, 2016). Children are those mostly confronted with take-home contamination in both developing and developed countries (Xiang Zeng et al., 2016). ● To date, little research has focused on workers' exposure or risk assessment in formal e-recycling. More studies are required to assess progress in occupational exposure following implementation of better protective measures in formal e-recycling and to evaluate improvements in environmental and human health exposure following a shift from informal activities to more formal ones in developing countries (Ceballos and Dong, 2016). ● Neither exposure assessment nor health risk assessment has been conducted among surrounding populations of formal e-recycling facilities in developed countries.
Understanding of the toxicology of chemical mixtures in e-recycling	● More studies are required to investigate potential inhibitory, synergistic or additive effects following multiple exposures to e-waste components in order to adequately assess human health risks (Grant et al., 2013). For example, experimental repeated exposure of earthworms to BDE-209/Pb (bromodiphenyl ether congener/lead) appears to increase the production of reactive oxygen species (ROS) (Hu et al., 2016). Another experiment led to contradictory results when assessing the interaction of Cd and flame retardant BDE-209 on blood cells with different evaluation methods (Curcic et al., 2017).
Better characterization of legacy contamination in developing countries	● China remains the focus of scientific interest due to its long informal e-recycling history and its position as a leading hub in the e-waste trade (Lines et al., 2016). However, there is growing concern about the prevalence of brominated flame retardants in various environmental matrices in other Asian countries (Mackintosh et al., 2015). ● Few field studies of environmental issues related to informal e-recycling have been conducted in India, which is surprising as it plays a non-negligible role in the current imported e-waste trade, after China (Borthakur and Singh, 2017). ● Ghana has been a focus of scientists with regard to its heavy contamination legacy, but the situation in other African countries, such as Nigeria, remains poorly documented. However, this country was involved in the hazardous waste trade early on and is becoming a hub for the second-hand market, while large open dumpsites are proliferating virtually everywhere (Peluola, 2016).
Characterization of legacy contamination related to e-waste landfilling and formal e-recycling in developed countries	● In developed countries, very few field studies similar to the work of Klees et al. (2017) (see Table 1 in Appendix A) have been carried out to date to address potential releases of e-waste contaminants from formal e-recycling facilities or landfill sites and their accumulation in the surrounding environment, despite calls for such research from a few authors (Ceballos and Dong, 2016; Seeberger et al., 2016). A human health and ecological risk assessment for e-recycling facilities conducted in Canada in 2004 had already underlined the need for further research on occupational health hazards related to e-waste contaminants, and for further environmental monitoring to assess potential risks for the surrounding population and environment (MJC and Associates, 2004). It is worth to mention that the increase in landfilling of CRT is already happening in the US as a response to the difficulty in processing the large quantities of CRT waste (Elliot, 2017).
Stronger body of evidence of adverse human health effects specifically ascribed to e-waste contaminants	● Cohort studies with sufficient sample sizes are required to explore the causal relationship between exposures to e-waste and detrimental health effects, especially among children and pregnant women subject to long-term exposure to e-waste contaminants. The existing epidemiological studies are descriptive and plagued by small numbers, sampling bias and inadequate adjustment for confounding factors (Grant et al., 2013; Xinjin Xu et al., 2015; Lin et al., 2016). ● No health studies have been done so far on formal e-recycling workers, in both developed and developing countries (Ceballos and Dong, 2016), or on populations surrounding formal e-recycling facilities and landfill sites in developed countries.

(*continued on next page*)

Table 4 (*continued*)

Knowledge gaps	Comments
More effective land decontamination technologies	● Remediation of e-waste contaminated lands is poorly documented, as field studies and full-scale applications are still overlooked (Duan et al., 2016). Available technologies are still at the experimental stage, including remediation of PCB-contaminated soils using plants (e.g., rice, alfalfa, ryegrass) (Shen et al., 2009), ultrasound-assisted soil washing to remove POPs and heavy metals (F. Chen et al., 2016), and bioremediation techniques using bacteria with the ability to absorb lead present in contaminated soil (Gayatri and Shailaja Raj, 2016).
Contribution of social factors in the increase of exposure and negative health outcomes among e-recycling workers.	● Some workers face increased risk for occupational injuries and illnesses as a result of social and economic structures historically linked to discrimination or exclusion. These are known as occupational health inequalities (Leong et al., 2017). ● By in large, e-waste recycling is conducted by workers from social marginalized groups such as prisoners, immigrants, ethnic minorities, and children. ● More research is needed to explore how social institutions such as racism, xenophobia, sexism, and classism materialize in the e-waste recycling industry and contribute to an increased risk of negative health outcomes for certain workers or segments of the general population (i.e. environmental justice) (NIOSH/ASSE, 2015). ● More research needs to be conducted on how the structure of the e-waste industry puts workers at greater risk for negative health outcomes. Topics of interest include how factors such as employment arrangements such as temporary employment or prison work impact worker safety. ● Similarly, the relationship between organizational factors - such as business size and formal/informal sectors – and worker health should be explored.

levels – with the ultimate goal of curbing the human health and environmental impacts of e-waste. Upstream solutions should address the crux of e-waste problems, which is a combination of a prevalent toxic potential, a relentless growth of e-waste volume that burdens collection logistics and proper e-recycling infrastructures, and a poor design that greatly complicates or even prevents recycling. Downstream solutions should ultimately lead to a gradual generalization of a proper, environmentally friendly and sustained e-recycling system that includes increased collection rates and safe final disposal of toxic parts and non-recyclable residuals. This remains the only way to divert e-waste from potentially harmful handling (including primitive recycling and direct landfilling and incineration with no prior decontamination), which is much more likely to expose workers and the general population to e-waste contaminants.

Although e-waste has become a global challenge, the policies needed to pave the way for future initiatives aimed at solving e-waste problems should be locally designed and go hand-in-hand with domestic realities. In other words, future policies regarding e-waste management should take into account some key parameters, such as the political, socio-economic, infrastructural, cultural and environmental contexts of each country involved (Borthakur and Govind, 2017). For instance, in India, current policy regarding e-waste management places more emphasis on EPR, while the e-recycling sector still lacks infrastructure and technology. Future policies should rather integrate all stakeholders involved in the recycling system, including informal scrap collectors and dismantlers (Awasthi and Li, 2017).

Thus, potential upstream solutions could include:

- **Substantially reducing the use of potentially toxic compounds**. Some substitutes for hazardous e-waste components already exist (e.g., lead-free alloys to replace traditional tin-lead solder, a nanoplate cobalt alloy instead of Cr, and carbon nanotubes to replace metal particles). However, a few substances such as Cd, Hg, Cr and flame retardants remain more challenging to replace in terms of physical and chemical properties. Furthermore, the affordability and functionality of safer materials remain the primary concern for e-product designers (Li et al., 2015; Meyer and Katz, 2016; You et al., 2016). Technology convergence, such as the integration of multiple devices into a single versatile one, may be an effective way to reduce human health and environmental impacts, provided that new devices replace as many single ones as possible (Son et al., 2015). Another avenue might be packaging designed to induce consumers to choose more environmentally friendly products (e.g., short description of chemical composition on e-product packaging) (You et al., 2016). Also, green electronics, which are still in the experimental phase, require further research and evaluation, global regulations, greater consumer awareness and stronger incentives (Verdecchia et al., 2017).
- **Decreasing quantities of e-waste**. To date, the main focuses have been on waste management and clean production. However, a promising new avenue is that of joint mobilization (including strong governmental involvement) against the functional and subjective obsolescence of e-products by endeavouring to increase both manufacturers' and consumers' accountability. A more visible relationship needs to be established between planned and subjective obsolescence and potentially negative health effects and environmental degradation, on both the local and global scales. Profound changes in consumption patterns are also in order, without infringing on the individual's right to consume. Education and awareness-raising initiatives should be undertaken on a broader scale to reach large audiences, with sensitization beginning during formal education as early as elementary school. Achieving a higher level of awareness would empower consumers to become change drivers who could push manufacturers towards more sustainable business approaches (Wilson et al., 2015; Ahmad Khan, 2016; Echegaray, 2016). Manufacturers also have a role to play in influencing consumer behaviours through more ethical attitudes and a lasting commitment to sustainable production. One of manufacturers' main contributions could be to ensure sustainable designs and optimize the feasibility of e-product repairs, thus guaranteeing a welcome increase in the lifespan of e-devices. Other possible solutions could include more flexible assembly modes such as bolt connections instead of rivet connections, standardized motherboards with fixed connections, better technical supervision of repairers and greater visibility for repair service shops (O'Connor et al., 2016; You et al., 2016; Sabbaghi et al., 2017). Studies have also shown the potential for a technical increase in e-products' lifespan: it is therefore incumbent upon manufacturers to encourage research and development in this promising area (Yadav et al., 2015). Besides technological adjustments, some authors suggest the optimization of e-waste reuse through implementation of an electronic inventory (e-inventory) management information system (MIS), especially among government departments and public establishments, identified as major e-product consumers in some

developing countries such as India. An e-inventory MIS would be helpful not only in precisely assessing e-waste generation, but also in standardizing purchase and disposal data on e-products. Thus, the e-inventory MIS would enable better supervision of e-product purchasing processes, particularly through better geographical location of old e-products within government and public offices, making them more readily available for reuse (Kumar and Rawat, 2015). In this context, it is worth underscoring the efforts of the European Parliament, which adopted a motion on "*a longer lifetime for products*" in June 2017, for the first time calling on the European Commission to legislate against planned obsolescence (European Parliament, 2017).

- **Increasing e-waste recyclability**. Many strategies have been suggested to promote eco-design right from the conception stage by adding an environmental dimension to the existing resource, thus improving the feasibility and added value of e-recycling processes. This includes concepts such as design for environment (DFE), design for recycling (DFR), design for disassembly (DFA), and design for recovery (DFR). Intended to increase the ease of both repair and recycling processes, these strategies are mostly based on modular designs integrating dismantling process facilitators (e.g., fewer screws, use of snap fits, metal frames instead of plastic ones, separable touch screens and batteries) and on optimal material compatibility when selecting material combinations based on both their recycling properties and their performance criteria (Li et al., 2016; Movilla et al., 2016; O'Connor et al., 2016; Zeng et al., 2017).

Potential downstream solutions could include:

- **Stopping the illegal trade while upgrading the informal e-recycling sector, pending full implementation of a safer formal sector**. These two actions go hand-in-hand, given that the illegal export of e-waste feeds informal practices. Engagement against the illegal e-waste trade is a shared concern of both exporting and receiving countries. It therefore calls for international cooperation and coordination, including harmonized customs control, along with better enforcement of domestic laws and regulations, and monitoring at both local and global levels. These steps would be further strengthened by the global expansion of improved and sustained formal collection and recycling activities (Huisman et al., 2015; Z. Wang et al., 2016c; Awasthi and Li, 2017). In developing countries, the formal e-recycling sector should effectively be supported by a stricter legal framework to ensure its broader implementation and expansion, and application of the best available technology (BAT) coupled with best environmental practices (BEP) (Awasthi and Li, 2017). However, even if there is a total ban, an informal e-recycling sector will continue to handle stockpiled imported and domestic e-waste. This remains a very important means of subsistence for low-income and less-educated populations. Cracking down on this sector by reinforcing regulation would do more harm than good, as unemployment would rise and hence degrade living and health conditions among already vulnerable populations. A more pragmatic solution would be to integrate informal activities into the recycling system by providing this sector with a better framework through efforts to increase awareness, education, training and occupational and environmental health guidance among informal workers, along with tools and technical and financial support (Amankwaa et al., 2016; Ardi and Leisten, 2016; Heacock et al., 2016). The "Best of two worlds" (Bo2W) model, developed by the multi-stakeholder Step Initiative, advocates a division of tasks such that a more protected informal sector in developing countries would take part only in manual dismantling activities (referred to as the "best" pre-processing), while the complex e-waste fraction laden with hazardous and valuable materials would be safely treated in state-of-the-art facilities located in developed countries (referred to as the "best" end-processing). Manual dismantling is thus considered more efficient and less costly for a higher yield of material liberation than the mechanical option. The Bo2W philosophy is seen as a transition measure and even as a "global reverse logistic" until such time as high-tech e-recycling facilities are fully implemented in developing countries (McCann and Wittmann, 2015; Wilson et al., 2015; Geeraerts et al., 2016; Singh et al., 2016). Some authors also support an "integrated system" approach that would efficiently connect already coexisting informal and formal sectors in some developing countries, if properly supported by a financial and legal framework along with government coordination. Collection and manual dismantling would also be handled by the informal sector, while the formal sector would manage safe metal recovery and final disposal (Chi et al., 2014). As mentioned earlier, the policy implications regarding e-waste management in developing countries should include the endorsement of suitable and practical e-waste policies that take into account socio-economic dynamics, while building on the integration of the informal sector into economic development rather than implementing punitive, and most likely ineffective, laws. Similarly, some authors also advocate a "*regulated green transboundary channel*" of e-waste between developed and developing countries to sustain the reuse market, in addition to dismantling activities, suggesting that exporting countries could also fund appropriate e-waste management in receiving countries (Milovantseva and Fitzpatrick, 2016). This action would be extremely relevant, given the quantity of still-operational devices stored at home in developed countries, as revealed by surveys conducted in Canada (Déméné and Marchand, 2016; Dewis and Van Wesenbeeck, 2016) and in the United Kingdom (Wilson et al., 2017). International cooperation is also suggested to support formal e-recycling in developing countries, mostly in terms of technology transfer and certification of facilities complying with legal and environmental criteria (Z. Wang et al., 2016c).
- **Introducing stronger and innovative reverse logistics to close the loop**. Reverse logistics encompasses the processes of recovering used goods. In the case of e-waste, it includes all the mechanisms implemented to encourage consumers to properly dispose of e-waste and return e-products to the manufacturers. Reverse logistics is a great concern for all countries. Advocated proactive actions include increasing consumers' knowledge and awareness of the human health and environmental risks associated with inappropriate practices, and boosting their willingness to be proactive (e.g., through participation in policy design and implementation, which includes more convenient modes of returning devices; and through multiplication of strategic collection points; environmentally oriented education to instill moral attitudes and behaviours; and use of social media and advertising campaigns). Other proactive actions could include the creation of more formalized jobs in collecting and sorting areas, together with the inclusion, education and training of informal workers, and the promotion of tax and credit incentives among manufacturers, retailers and formal collectors (Dixit and Badgaiyan, 2016; Grant and Oteng-Abadio, 2016; Gu et al., 2016; Guarnieri et al., 2016; Liang and Sharp, 2016; Kumar et al., 2017). In developed countries, better cooperation between the private and public sectors could be more productive as competitive collection systems may play a more significant role in improving collection rates from households than single or non-competitive collection systems (Corsini et al., 2017).
- **Upgrading formal e-recycling processes**. Intensive research is currently under way to enhance e-recycling technologies, in terms of environmental performances and profitability, in order to ensure optimal recovery of valuable materials and thus reduce pressure on the demand for raw materials, to create sustainable businesses and jobs, to treat hazardous fractions in an environmentally sound manner, and ultimately to dispose of e-waste properly (Kumari et al., 2016; Li et al., 2016; Movilla et al., 2016; Tansel, 2017). Improving environmental performances is not necessarily

incompatible with optimal efficiency. Iannicelli-Zubiani et al. (2017) have shown that environmental impacts of the hydrometallurgical process could be decreased without affecting its efficiency, simply by expanding the lifetime of the sorbents used during the adsorption steps to achieve precious material separation and recovery. However, rather than using only one e-recycling technology, various technologies (i.e., acid leaching processes, pyrometallurgy, vacuum metallurgy, and electrometallurgy) should be combined and integrated to address the complexity of physical and chemical properties of e-waste, and thus to optimize recovery efficiency and environmental performances (Zhang and Xu, 2016). For example, Kumari et al. (2016) found that a thermal pre-treatment process (pyrolysis) of low metal concentrate waste from printed circuit boards combined with physical beneficiation and hydrometallurgical processes is beneficial both ecologically and economically. Thus, such pre-treatment makes the hydrometallurgical process much easier and more effective, while the overall process becomes more eco-friendly by incorporating the “zero waste generation concept”.

Banning the export of e-waste would undoubtedly provide a strong incentive to improve e-recycling processes. In these times of scarce resources and environmental degradation (Ryneal, 2016; Tansel, 2017), upgrading formal e-recycling processes would be doubly advantageous, given the great economic development and profitability potential and the gainful employment opportunities they offer in developing countries (Amankwah-Amoah, 2016; Ryneal, 2016), as well as in developed countries (Cucchiella et al., 2016).

6. Conclusion

To the best of our knowledge, this is the first paper to adopt a holistic approach that exposes the extreme complexity of the issues, challenges and gaps (including human health concerns and environmental degradation) associated with the tricky e-waste question, and that suggests potential solutions, both upstream and downstream. The many initiatives launched thus far to advocate suitable management practices are facing disappointing realities, which are reflected in heavy legacy contamination and significant human exposure to e-waste contaminants in workers and surrounding populations in both formal and informal e-recycling activities. Exploring e-waste issues is akin to opening a Pandora's box, with constantly emerging e-waste legacy contamination issues regarding, for example, critical exposure pathways, unexpected sources and environmental fates of contaminants, as well as newly detected e-waste contaminants, all of which is further complicated by an increasingly intricate illegal e-waste trade.

However, despite scientific gaps, current knowledge of the threats posed by persistent and bioaccumulative pollutants is sufficient to raise awareness and concern among all stakeholders. Upstream solutions for e-waste issues should focus on reducing the use of potentially toxic compounds, in particular, by promoting technologies for green electronics; decreasing e-waste volume through the environmentally oriented consumer education and sustained commitments from manufacturers to counter planned and subjective obsolescence; and increasing e-waste recyclability mostly through modular design and optimal material compatibility. At the downstream level, solutions should focus on taking suitable and pragmatic actions to progressively reduce the illegal e-waste trade, particularly through international cooperation; better enforcement of domestic laws; and monitoring, along with the supervised integration of the informal sector into the recycling system and global expansion of formal e-waste collection and recycling activities. Downstream solutions should also include specific efforts to improve e-recycling technologies in terms of efficiency, affordability and environmental performance, in particular, by combining and integrating various recycling technologies to address e-waste complexity, given the great economic potential of e-recycling and its key role in preventing the incineration and/or landfilling of e-waste.

Human health (including worker health) and environmental integrity can quite conceivably be preserved while safely and wisely managing e-waste resources. However, achieving this goal may require an ideological shift towards a perception of e-waste as a vital input that could be re-introduced into other processes. This would effectively keep the lid on Pandora's box.

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Disclaimer

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Appendix A

Table 1
Recent reports on environmental and human burdens ascribed to e-waste contaminants.

Nature of activities, sampling site	Environmental matrices sampled and dates	Targeted contaminants	Reported outcomes	Human health assessment	References
Informal small dismantling workshops and factories in the city of Guiyu[a] (China)	Topsoil and riverine sediment within Guiyu and adjacent towns February 2009	PAHs	High concentration of PAHs compared to rural soils elsewhere in China. Concentrations of PAHs higher in sediments compared to soils.	Relatively high carcinogenic risks associated with PAHs in riverine sediments through soil ingestion, dermal absorption and particulates inhalation.	P. Xu et al. (2016)
	Air in the vicinity of open burning and crude recycling March 2012 to April 2013	Heavy metals	Larger $PM_{2.5}$ concentrations than in other Asian cities, with higher heavy metal concentrations during winter and spring.	– Total potential cancer risk for both adults and children higher than US EPA recommendations. – Higher public health risk for children than adults, with regard to	Xiangbin Zheng et al. (2016c)

				carcinogenic and non-carcinogenic elements in $PM_{2.5.}$	
Informal e-recycling industrial park, in a collection of small villages around Taizhou (Zhejiang, China)	Soil, paddy seeds (hulls and unpolished rice), apple snails. Sampling area of 65-km radius around Taizhou. 2008 and 2010	Short-chain chlorinated paraffins (SCCPs)[b]	Higher concentrations in snails and rice grain hulls (part of the feed formulation of pigs and chickens on local farms) than in soil and unpolished rice.	Elevated risks via dietary exposure to SCCPs for people living in the e-recycling area.	Yuan et al. (2017)
Informal e-recycling sites (Southern China)	Indoor dust September 2013 and March 2014	PCBs PBDEs DBDPE DPs Heavy metals	High concentrations of organic pollutants and heavy metals (except for Zn) in e-recycling areas.	– Excessive estimated daily intakes (EDIs) of PCBs, PBDEs, DBDPE, and DPs for adults in the e-waste recycling area (respectively 5.7–18.6 times and 4.1–85.5 times higher than those in rural and urban areas). – An EDI of Cd in the e-waste recycling 11.8 to 19.8 times higher than that in rural and urban areas. – An EDI of Pb 18 times higher than the Pb reference dose.	He et al. (2017)
Informal e-recycling Zhejiang Province (China)	620 foods collected between 2006 and 2015 mainly from Zhejiang market and e-waste dismantling areas.	PCDD/Fs PCBs	High concentrations of PCDD/Fs and PCBs in all foods sampled.	High human risk in the worst case scenario (only highly contaminated foods consumed). Estimated dietary intake for local residents approximatively 3.5-fold greater than the standard toxic equivalent (TEQ).	Shen et al. (2017)
Informal e-recycling workshops and open burning facilities Agbogbloshie (Ghana) (one of the world's largest e-recycling areas)	Soil in workshops and open burning areas 2015	PAHs	Predominance of phenanthrene, fluoranthene and pyrene.	Elevated carcinogenic risk in case of prolonged exposure via multiple pathways	Daso et al. (2016)
		PBDEs Heavy metals	Notable presence of PBDEs in surface soils; BDE-28 congener predominant. Moderate to extreme pollution by metals.	With moderate and maximum exposure scenarios via ingestion: significant non-carcinogenic health risk of local PBDE (BDE-47 and BDE-99 congeners) exposure for children and adverse health predicted for both adults and children with regard to Cu and Pb.	Akortia et al. (2017)
Informal metal recovery or dismantling workshops, nearby highway in urban centers and suburban industrial roadsides in Chennai City (India)	Dust from workshops and nearby other sample points May 2014	PCBs	Concentration of PCBs in settled dust from informal metal recovery workshops tenfold higher than in urban centre.	– Major exposure routes for PCBs: dermal contact, ingestion (hand-to-mouth) and dust inhalation. – High cancer risk in e-recycling workshops for children via ingestion exposure. – Ingestion and dermal contact risk in e-recycling workshops exceeding Canadian threshold limit for a	Chakraborty et al. (2016)

				public health concern (1×10^{-6}).	
Informal e-recycling area Ogunpa Market, Ibadan (Nigeria)	Soil from different depths (within recycling and open burning sites) Unspecified period	Heavy metals and metalloids	Heavy contamination, with average concentrations of Pb and Cu exceeding soil regulatory limits. 65% of Cu and 88% of Pb susceptible to potential mobility.		Adesokan et al. (2016)
Informal e-recycling site Meycauayan, Bulacan operating for > 30 years (The Philippines)	Surface soil within e-recycling area January 2012	Heavy metals	High concentrations of Pb and Cu, especially near smelting area and stockyard.		Terazono et al. (2017)
Informal e-recycling in workshops among residences Sue Yai Utit, Bangkok (Thailand)	Surface soil (within e-dismantling site and in adjacent areas) August 2014	Heavy metals	High contamination levels of Cu, Ni, Pb, and Zn, in both fine and coarse soil particles.		Damrongsiri et al. (2016)
Backyard informal e-recycling areas, often within 20 m of living area Bui Dau village, Hung Yen province, (North Vietnam)	Fish (from ponds and canals close to workshops), sediment (drainage canals of water flow near families having workshops), house dust (surface of furniture and fan blades in the houses) 2013–2015	Flame retardants PBDEs	*Fish*: High concentrations of PBDEs compared to other fish collected in some farming facilities. *Sediments*: High concentrations of PBDEs compared to sediments collected from other industrial areas. *House dust*: High concentrations of PBDEs (BDE-99 and BDE-209) compared to house dust in Australia or Canada (but lower than indoor dust from e-waste recycling sites in China).	– Intakes of PBDEs, especially BDE-99 and BDE-209 congeners, higher via fish consumption than intakes via dust ingestion. – Higher range of body weight normalizing daily intake through dust ingestion than those reported in other countries.	Anh et al. (2016)
The surroundings and the premises of formal e-recycling facilities in North-Rhine Westphalia, Germany	Curly kale and spruce needles from the residential area around the formal facility Street dust from or near the access roads to the facilities Dust from the premises 2014 and 2015	PCBs	*Curly kale and spruce needles*: High PCB concentrations directly north of the industrial premises. Evident concentration gradient from the industrial premises to the residential areas located southwest and northeast. *Street dust and dust*: High PCB contamination. Homologue patterns of highly PCB-contaminated dusts and street dusts similar to the homologue patterns of PCBs in curly kale and spruce needles.		Klees et al. (2017)

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[a] Informal activities have been suspended in Guiyu since December 2015 (Ceballos and Dong, 2016).

[b] The inclusion of SCCPs as persistent organic pollutants (POPs) in the Stockholm Convention is under review (Yuan et al., 2017).

Table 2
Recent reports on the body burden of e-waste contaminants in e-recycling workers and surrounding populations.

Study population	Nature of activities, sampling site	Type of sample and date	Targeted contaminants	Reported outcomes	References
Workers	Informal e-recycling Longtang, Qingyuan City (China)	Hair and serum 2010	DPs	– Elevated serum and hair DPs levels. – Positive correlation between hair DPs levels and serum DPs levels in paired samples.	Chen et al. (2015)
	Informal e-recycling (Southern China)	Hair and serum July 2011	PCBs	– Elevated serum and hair PCB levels. – Positive correlation between hair PCB levels and serum PCB levels in paired samples.	J. Zheng et al. (2016)
Surrounding population	Informal e-recycling Guiyu (China)	Hair from people living and/or working in the e-recycling area April–June 2012	Sb	– Higher Sb levels than at control site. – Higher Sb levels for people in e-recycling activities. – Main factors associated with high Sb levels: e-recycling work and long-term residence in Guiyu.	Huang et al. (2015)
		Human placental tissues March and August 2012	PBDEs	Higher PBDE levels in placenta from women residing in Guiyu compared to control population.	L. Xu et al. (2015)
			Cd, Pb	Placental Pb and Cd levels higher in the e-recycling area.	L. Xu et al. (2016)
		Children's blood 2012	Heavy metals and metalloids	High levels of Pb, Ni, Cu, Zn, and Se in exposed children compared to reference group living in a fishing town.	Lin et al. (2017)
	Informal e-recycling Taizhou (China)	Breast milk of women living within the e-recycling area From 2012 to 2013	PBDEs, hydroxylated polychlorinated biphenyls (OH-PBDEs), 2,2′,4,4′,5,6′-hexachlorobiphenyl (CB-153)	– High median levels of PBDEs in breast milk from residents living in e-recycling areas via dietary exposure. – Great concern about potential effect on development of neonates over long-term exposure.	Li et al. (2017)
	Informal e-recycling Longtang Town (China)	Urine July–August 2014	Bisphenols A (BPA), F (BPF) and S (BPS)	Urinary levels of BPA and BPF significantly higher in residents of e-reycling area compared to reference rural residents.	Zhang et al. (2016)
Workers	CRT televisions Formal recycling (France)	Personal air and ambient air in a CRT recycling unit 2007–2011	Heavy metals	– High levels of pollution exceeding some French Ministry of Labour occupational exposure limits – Personal Pb dust exposure levels higher than the ambient levels in sampled facilities.	Lecler et al. (2015)
Workers	Informal e-recycling Agbogbloshie (Ghana)	Blood October 2011	PCDD/Fs, PCBs	PCDD/Fs blood levels related to the e-waste burning activities.	Wittsiepe et al. (2015)
		Blood 2014	Pb	Blood Pb levels over five times higher than average levels in the US.	Carlson (2016)
		Blood, urine April 2014	Heavy metals	– Blood Cd and Pb levels and urinary As level higher than in reference group. – Urinary As level above the US Agency for Toxic Substances and Disease Registry (ATSDR) limit.	Srigboh et al. (2016)

				– Highest biomarker levels among workers involved in e-waste open burning.	
Workers	Formal recycling (Sweden)	Blood, urine, plasma 2007–2009	Heavy metals	Higher blood, urine, and/or plasma levels of Cr, Co, Hg, In, Pb in recycling workers, compared to office workers.	Julander et al. (2014)
Workers	Formal e-recycling Unspecified location (3 facilities in the United States)	Blood, urine, personal air, surface and skin wipes January, February, April, June, September 2013 and February 2014	Heavy metals	– One exposure to Pb and two exposures to Cd above the respective Occupational Safety and Health Administration Permissible Exposure Limit (OSHA PEL) – High blood Pb levels for some dismantler employees – Presence of heavy metals on the skin and clothing of employees	Ceballos et al. (2017)
Surrounding population	Informal e-reycling (burning cables) in Montevideo (Uruguay)	Blood from children and adolescents involved in burning cables and gathering metals 2010–2014	Pb	– Blood Pb levels higher than recommended level of 5 μg/dL for medical intervention (microgram per deciliter) – High blood lead levels among youngest children (often playing in the ground where cables are burned)	Pascale et al. (2016)
Workers	Informal e-recycling Bui Dau (Vietnam)	Serum 2010–2011	Organohalogen compounds: PCBs, OH-PCBs, PBDEs, methoxylated polybrominated diphenyl ether (MeO-PBDEs), OH-PBDEs, bromophenols (BPhs)	Higher serum residue levels of PCBs, OH-PCBs, PBDEs, and BPhs in e-recycling workers compared to blood donors from a rural site	Eguchi et al. (2015)

References

Adesokan, M.D., Adie, G.U., Osibanjo, O., 2016. Soil pollution by toxic metals near e-waste recycling operations in Ibadan, Nigeria. J. Health Pollut. 6 (11), 26–33.

Ahmad Khan, S., 2016. E-products, e-waste and the Basel Convention: regulatory challenges and impossibilities of international environmental law. RECIEL. 25 (2), 248–260.

Akortia, E., Olukunle, O.I., Daso, A.P., Okonkwo, J.O., 2017. Soil concentrations of polybrominated diphenyl ethers and trace metals from an electronic waste dump site in the Greater Accra Region, Ghana: implications for human exposure. Ecotoxicol. Environ. Saf. 137, 247–255.

Amankwaa, E.F., Bowman, J., Tsikudo, K.A., 2016. Recyclers at risk? Analysis of e-waste livelihoods and blood lead levels at Ghana's recycling hub. In: Agbogbloshie. Policy Brief 33113, June 2016. International Growth Center. http://www.theigc.org/wp-content/uploads/2016/07/Amankwaa-Tsikudo-2016-Policy-brief.pdf, Accessed date: 1 October 2017.

Amankwah-Amoah, J., 2016. Global business and emerging economies: towards a new perspective on the effects of e-waste. Technol. Forecast. Soc. 105, 20–26.

American Chemistry Council, 2017. Classes of Flame Retardants: North American Flame Retardant Alliance. https://flameretardants.americanchemistry.com/Classes-of-FRs, Accessed date: 5 December 2017.

An, T., Huang, Y., Li, G., He, Z., Chen, J., Zhang, C., 2014. Pollution profiles and health risk assessment of VOCs emitted during e-waste dismantling processes associated with different dismantling methods. Environ. Int. 73, 186–194.

Andrews, A., 2009. Beyond the ban – can the basel convention adequately safeguard the interests of the world's poor in the international trade of hazardous waste? LEAD J. 5 (2), 167. http://www.lead-journal.org/content/09167.pdf, Accessed date: 5 December 2017.

Anh, H.Q., Nam, V.D., Tri, T.M., Ha, N.M., Ngoc, N.T., Mai, P.T.N., et al., 2016. Polybrominated diphenyl ethers in plastic products, indoor dust, sediment and fish from informal e-waste recycling sites in Vietnam: a comprehensive assessment of contamination, accumulation pattern, emissions, and human exposure. Environ. Geochem. Health 1–20. http://dx.doi.org/10.1007/s10653-016-9865-6.

Ardi, R., Leisten, R., 2016. Assessing the role of informal sector in WEEE management systems: a system dynamics approach. Waste Manag. 57, 3–16.

Asampong, E., Dwuma-Badu, K., Stephens, J., Srigboh, R., Neitzel, R., Basu, N., Fobil, J.N., 2015. Health seeking behaviours among electronic waste workers in Ghana. BMC Public Health 15, 1065.

Aschberger, K., Campia, I., Pesudo, L.Q., Radovnikovic, A., Reina, V., 2017. Chemical alternatives assessment of different flame retardants – a case study including multi-walled carbon nanotubes as synergist. Environ. Int. 101, 27–45.

ATSDR (Agency for Toxic Substances & Disease Registry), 2017. ATSDR Toxic Substances Portal. Last updated March 23, 2017. https://www.atsdr.cdc.gov/toxfaqs/index.asp, Accessed date: 26 May 2017.

Awasthi, A.K., Li, J., 2017. Management of electrical and electronic waste: a comparative evaluation of China and India. Renew. Sust. Energ. Rev. 76 (Supplement C), 434–447.

Awasthi, A.K., Zeng, X., Li, J., 2016. Environmental pollution of electronic waste recycling in India: a critical review. Environ. Pollut. 211, 259–270.

Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. Global e-Waste Monitor – 2014. United Nations University, IAS – SCYCLE, Bonn, Germany. https://i.unu.edu/media/ias.unu.edu-en/news/7916/Global-E-waste-Monitor-2014-small.pdf, Accessed date: 1 October 2017.

BAN/SVTC (Basel Action Network/Silicon Valley Toxics Coalition), 2002. Exporting Harm, the High-Tech Trashing of Asia. https://static1.squarespace.com/static/558f1c27e4b0927589e0edad/t/56184364e4b0cf5700f852af/1444430692735/Exporting+Harm+Report.pdf, Accessed date: 15 May 2017.

Basel Convention, 2011. Reports and Decisions. Decision IV/9 Adopted by the Conference of the Parties at its Fourth Meeting, 6 May 1998. http://basel.int/TheConvention/ConferenceoftheParties/ReportsandDecisions/tabid/3303/Default.aspx, Accessed date: 1 October 2017.

Basel Convention, 2017. Amendment to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, Official website. http://www.basel.int/Countries/StatusofRatifications/BanAmendment/tabid/1344/Default.aspx, Accessed date: 5 February 2017.

Bellanger, M., Demeneix, B., Grandjean, P., Zoeller, R.T., Trasande, L., 2015. Neurobehavioral deficits, diseases, and associated costs of exposure to endocrine-disrupting chemicals in the European Union. J. Clin. Endocrinol. Metab. 100 (4), 1256–1266.

Borthakur, A., Govind, M., 2017. Emerging trends in consumers' E-waste disposal behaviour and awareness: a worldwide overview with special focus on India. Resour. Conserv. Recycl. 117 (Part B), 102–113.

Borthakur, A., Singh, P., 2017. Researches on informal e-waste recycling sector: it's time for a 'Lab to Land' approach. J. Hazard. Mater. 323 (Part B), 730–732.

Bradford, M., 2011. The United States, China & the Basel Convention on the transboundary movements of hazardous wastes and their disposal. Fordham Environ. Law Rev. 8 (2), 305–349. http://ir.lawnet.fordham.edu/cgi/viewcontent.cgi?article=1445&context=elr, Accessed date: 26 May 2017.

Carlson, K., 2016. Electronic waste worker health: studying complex problems in the real world. In: Proceeding from the Eighth International Conference on Information and Communication Technologies and Development (ICTD), Article No. 35, Ann Arbor, Michigan, USA [June 3-6], ACM 978-1-4503-4306-0/16/06.

Cayumil, R., Khanna, R., Rajarao, R., Ikram-ul-Haq, M., Mukherjee, P.S., Sahajwalla, V., 2016. Environmental impact of processing electronic waste – key issues and challenges. In: Mihai, F.C. (Ed.), E-waste in Transition - From Pollution to Resource. InTech, Croatia, pp. 9–35.

Ceballos, D.M., Dong, Z., 2016. The formal electronic recycling industry: challenges and opportunities in occupational and environmental health research. Environ. Int. 95, 157–166.

Ceballos, D., Beaucham, C., Page, E., 2017. Metal exposure at three U.S. electronic scrap recycling facilities. J. Occup. Environ. Hyg. 14 (6), 401–408.

Chakraborty, P., Prithiviraj, B., Selvaraj, S., Kumar, B., 2016. Polychlorinated biphenyls in settled dust from informal electronic waste recycling workshops and nearby highways in urban centers and suburban industrial roadsides of Chennai city, India: levels, congener profiles and exposure assessment. Sci. Total Environ. 573, 1413–1421.

Chen, A., Dietrich, K.N., Huo, X., Ho, S.M., 2011. Developmental neurotoxicants in e-waste: an emerging health concern. Environ. Health Perspect. 119 (4), 431–438.

Chen, K., Zheng, J., Yan, X., Yu, L., Luo, X., Peng, X., et al., 2015. Dechlorane Plus in paired hair and serum samples from e-waste workers: correlation and differences. Chemosphere 123, 43–47.

Chen, Fu, Yang, B., Ma, J., Qu, J., Liu, G., 2016. Decontamination of electronic waste-polluted soil by ultrasound-assisted soil washing. Environ. Sci. Pollut. R. 23 (20), 20331–20340.

Chen, Jiangyao, Huang, Y., Li, G., An, T., Hu, Y., Li, Y., 2016. VOCs elimination and health risk reduction in e-waste dismantling workshop using integrated techniques of electrostatic precipitation with advanced oxidation technologies. J. Hazard. Mater. 302, 395–403.

Chi, X., Wang, M.Y.L., Reuter, M.A., 2014. E-waste collection channels and household recycling behaviors in Taizhou of China. J. Clean. Prod. 80 (Supplement C), 87–95.

Corsini, F., Rizzi, F., Frey, M., 2017. Extended producer responsibility: the impact of organizational dimensions on WEEE collection from households. Waste Manag. 59, 23–29.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sust. Energ. Rev. 51, 263–272.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2016. A profitability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments. Renew. Sust. Energ. Rev. 64, 749–760.

Cui, J.L., Luo, C.L., Tang, C.W.Y., Chan, T.S., Li, X.D., 2017. Speciation and leaching of trace metal contaminants from e-waste contaminated soils. J. Hazard. Mater. 329, 150–158.

Cummings, K.J., Nakano, M., Omae, K., Takeuchi, K., Chonan, T., Xiao, L., et al., 2012. Indium lung disease. Chest 141 (6), 1512–1521.

Curcic, M., Buha, A., Stankovic, S., Milovanovic, V., Bulat, Z., Đukić-Ćosić, D., et al., 2017. Interactions between cadmium and decabrominated diphenyl ether on blood cells count in rats—multiple factorial regression analysis. Toxicology 376, 120–125.

D'Adamo, I., Paolo, R., Terzi, S., 2016. Challenges in waste electrical and electronic equipment management: a profitability assessment in three European countries. Sustain. For. 8 (633).

Damrongsiri, S., Vassanadumrongdee, S., Tanwattana, P., 2016. Heavy metal contamination characteristic of soil in WEEE (waste electrical and electronic equipment) dismantling community: a case study of Bangkok, Thailand. Environ. Sci. Pollut. Res. 23 (17), 17026–17034.

Daso, A.P., Akortia, E., Okonkwo, J.O., 2016. Concentration profiles, source apportionment and risk assessment of polycyclic aromatic hydrocarbons (PAHs) in dumpsite soils from Agbogbloshie e-waste dismantling site, Accra, Ghana. Environ. Sci. Pollut. Res. 23, 10883–10894.

Déméné, C., Marchand, A., 2016. Exploring users' practices through the use phase of a television to minimise the environmental impact. J. Res. Consumers 29, 4–13. http://www.jrconsumers.com/Consumer_Articles/issue_29/, Accessed date: 1 October 2017.

Dewis, G., Van Wesenbeeck, P., 2016. Trash Talking - Dealing With Canadian Household E-waste EnviroStats: Statistics Canada. Catalogue 16-002-X. http://www.statcan.gc.ca/pub/16-002-x/2016001/article/14570-eng.pdf, Accessed date: 30 May 2017.

Dixit, S., Badgaiyan, A.J., 2016. Towards improved understanding of reverse logistics – examining mediating role of return intention. Resour. Conserv. Recycl. 107, 115–128.

Du, H., Yu, M., Sun, J., Song, G., Li, Y., 2016. Epidemiological evidence of the effects of environmental pollution on male reproductive health in an electronic waste-recycling town. Pol. J. Environ. Stud. 25 (4), 1777–1780.

Duan, H., Hu, J., Tan, Q., Liu, L., Wang, Y., Li, J., 2016. Systematic characterization of generation and management of e-waste in China. Environ. Sci. Pollut. Res. Int. 23 (2), 1929–1943.

Echegaray, F., 2016. Consumers' reactions to product obsolescence in emerging markets: the case of Brazil. J. Clean. Prod. 134, 191–203.

Echegaray, F., Hansstein, F.V., 2017. Assessing the intention-behavior gap in electronic waste recycling: the case of Brazil. J. Clean. Prod. 142, 180–190.

Edwards, L., 2016. E-waste Recycling: The Dirty Trade Between the United States and China. Pomona Senior Theses. Paper 153. http://scholarship.claremont.edu/pomona_theses/153, Accessed date: 1 December 2017.

Eguchi, A., Nomiyama, K., Minh Tue, N., Trang, P.T., Hung Viet, P., Takahashi, S., Tanabe, S., 2015. Residue profiles of organohalogen compounds in human serum from e-waste recycling sites in North Vietnam: association with thyroid hormone levels. Environ. Res. 137, 440–449. http://dx.doi.org/10.1016/j.envres.2015.01.007.

Elliot, B., 2016. Bankrupt Processor Leaves Behind CRTs, E-Scrap News, Posted on March 10, 2016. https://resource-recycling.com/e-scrap/2016/03/10/bankrupt-processor-leaves-behind-crts/, Accessed date: 8 June 2017.

Elliot, B., 2017. Landfilling CRT Glass Becomes the Norm in California. E-scrap News, Posted on March 2, 2017. https://resource-recycling.com/e-scrap/2017/03/02/landfilling-crt-glass-becomes-norm-california/, Accessed date: 8 June 2017.

European Commission, 2017. Waste Electrical & Electronic Equipment (WEEE). Last Updated 2017/04/24. http://ec.europa.eu/environment/waste/rohs_eee/legis_en.htm, Accessed date: 1 December 2017.

European Parliament, 2017. Report on a Longer Lifetime for Products: Benefits for Consumers and Companies (2016/2272(INI)). Committee on the Internal Market and Consumer Protection, 9 June 2017. http://www.europarl.europa.eu/sides/getDoc.do?pubRef = -//EP//TEXT + REPORT + A8-2017-0214 + 0 + DOC + XML + V0//EN#title2, Accessed date: 24 July 2017.

Flynn, M.A., 2014. Safety and the diverse workforce: lessons from NIOSH's work with Latino immigrants. Prof. Saf. 59 (6), 52–57.

Fornalczyk, A., Willner, J., Francuz, K., Cebulski, J., 2013. E-waste as a source of valuable metals. Arch. Mater. Sci. Eng. 63 (2), 87–92.

Fujimori, T., Takigami, H., 2014. Pollution distribution of heavy metals in surface soil at an informal electronic-waste recycling site (Philippines). Environ. Geochem. Health 36, 159–168.

Fujimori, T., Takigami, H., Agusa, T., Eguchi, A., Bekki, K., Yoshida, A., et al., 2012. Impact of metals in surface matrices from formal and informal electronic-waste recycling around Metro Manila, the Philippines, and intra-Asian comparison. J. Hazard. Mater. 221–222, 139–146.

Fujimori, T., Itai, T., Goto, A., Asante, K.A., Otsuka, M., Takahashi, S., Tanabe, S., 2016. Interplay of metals and bromine with dioxin-related compounds concentrated in e-waste open burning soil from Agbogbloshie in Accra, Ghana. Environ. Pollut. 209, 155–163.

Gayatri, Y., Shailaja Raj, M., 2016. Molecular characterization of bacteria isolated from e-waste dumping yards at Hyderabad, Telangana, India. Eur. J. of Ex. Biol. 6 (6), 1. https://www.imedpub.com, Accessed date: 1 December 2017.

Geeraerts, K., Illes, A.I., Schweizer, J.P., 2016. Illegal Shipment of E-Waste From the EU: A Case Study on Illegal E-Waste Export From the EU to China. A Study Compiled as Part of the EFFACE project. IEEP, Institute for European Environmental Policy, London. http://efface.eu/sites/default/files/EFFACE_Illegal%20shipment%20of%20e%20waste%20from%20the%20EU.pdf, Accessed date: 30 May 2017.

Ghosh, S.K., Debnath, B., Baidya, R., De, D., Li, J., Ghosh, S.K., et al., 2016. Waste electrical and electronic equipment management and Basel Convention compliance in Brazil, Russia, India, China and South Africa (BRICS) nations. Waste Manag. Res. 34 (8), 693–707.

Gramatica, P., Cassani, S., Sangion, A., 2016. Are some “safer alternatives” hazardous as PBTs? The case study of new flame retardants. J. Hazard. Mater. 306, 237–246.

Grant, R.J., Oteng-Abadio, M., 2016. The global transformation of materials and the emergence of informal urban mining in Accra, Ghana. Africa Today 62 (4), 2–20. Published by Indiana University Press. https://muse.jhu.edu/article/620263, Accessed date: 30 May 2017.

Grant, K., Goldizen, F.C., Sly, P.D., Brune, M.-N., Neira, M., van den Berg, M., Norman, R.E., 2013. Health consequences of exposure to e-waste: a systematic review. Lancet Glob. Health 1 (6), e350–e361.

Gu, Y., Wu, Y., Xu, M., Wang, H., Zuo, T., 2016. The stability and profitability of the informal WEEE collector in developing countries: a case study of China. Resour. Conserv. Recycl. 107, 18–26.

Guarnieri, P., e Silva, L.C., Levino, N.A., 2016. Analysis of electronic waste reverse logistics decisions using strategic options development analysis methodology: a Brazilian case. J. Clean. Prod. 133, 1105–1117.

Guna, V.K., Murugesan, G., Basavarajaiah, B.H., Ilangovan, M., Olivera, S., Krishna, V., Reddy, N., 2016. Plant-based completely biodegradable printed circuit boards. IEEE Trans. Electron Devices 63 (12), 4893–4898.

Haque, N., Hughes, A., Lim, S., Vernon, C., 2014. Rare earth elements: overview of mining, mineralogy, uses, sustainability and environmental impact. Resources 3, 614–635.

He, C.T., Zheng, X.B., Yan, X., Zheng, J., Wang, M.H., Tan, X., et al., 2017. Organic contaminants and heavy metals in indoor dust from e-waste recycling, rural, and urban areas in South China: spatial characteristics and implications for human exposure. Ecotoxicol. Environ. Saf. 140, 109–115.

Heacock, M., Kelly, C.B., Suk, W.A., 2016. E-waste: the growing global problem and next steps. Rev. Environ. Health 31 (1), 131–135.

Honda, S., Khetriwal, D.S., Kuehr, R., 2016. Regional E-waste Monitor: East and Southeast Asia. United Nations University ViE – SCYCLE, Bonn, Germany. http://ewastemonitor.info/pdf/Regional-E-Waste-Monitor.pdf, Accessed date: 30 May 2017.

Hong, W.J., Jia, H., Ding, Y., Li, W.L., Li, Y.F., 2016. Polychlorinated biphenyls (PCBs) and halogenated flame retardants (HFRs) in multi-matrices from an electronic waste (e-waste) recycling site in Northern China. J. Mater. Cycles Waste Manage. 1–11.

Hopson, E., Puckett, J., 2016. Scam Recycling: e-Dumping on Asia by US Recyclers. The e-Trash Transparency Project, Basel Action Network. https://www.resource-recycling.com/images/BANReportTwo.pdf, Accessed date: 30 May 2017.

Hu, S., Zhang, W., Li, J., Lin, K., Ji, R., 2016. Antioxidant and gene expression responses of Eisenia fetida following repeated exposure to BDE209 and Pb in a soil-earthworm system. Sci. Total Environ. 556, 163–168.

Huang, Y., Ni, W., Chen, Y., Wang, X., Zhang, J., Wu, K., 2015. Levels and risk factors of antimony contamination in human hair from an electronic waste recycling area, Guiyu, China. Environ. Sci. Pollut. Res. 22 (9), 7112–7119.

Huisman, J., Botezatu, I., Herreras, L., Liddane, M., Hintsa, J., di Cortemiglia, Luda, et al., 2015. Countering WEEE Illegal Trade (CWIT) Summary Report, Market Assessment, Legal Analysis, Crime and Recommendations Roadmap, August 30, 2015. Lyon, France. https://www.interpol.int/content/download/32151/417087/version/1/file/CWIT%203%20small.pdf, Accessed date: 30 May 2017.

Iannicelli-Zubiani, E.M., Giani, M.I., Recanati, F., Dotelli, G., Puricelli, S., Cristiani, C., 2017. Environmental impacts of a hydrometallurgical process for electronic waste treatment: a life cycle assessment case study. J. Clean. Prod. 140 (Part 3), 1204–1216.

IARC (International Agency for Research on Cancer), 2017. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. http://monographs.iarc.fr/index.php, Accessed date: 30 May 2017.

Interpol, 2009. Electronic Waste and Organized Crime - Assessing the Link - Phase II Report for the Interpol Pollution Crime Working Group: Interpol Pollution Crime Working Group. https://www.interpol.int/content/download/5367/45070/version/3/file/Wastereport.pd, Accessed date: 30 May 2017.

Iqbal, M., Breivik, K., Syed, J.H., Malik, R.N., Li, J., Zhang, G., Jones, K.C., 2015. Emerging issue of e-waste in Pakistan: a review of status, research needs and data gaps. Environ. Pollut. 207, 308–318.

Julander, A., Lundgren, L., Skare, L., Grandér, M., Palm, B., Vahter, M., Lidén, C., 2014. Formal recycling of e-waste leads to increased exposure to toxic metals: an occupational exposure study from Sweden. Environ. Int. 73, 243–251.

Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an overview. Waste Manag. 33 (5), 1237–1250.

Klaassen, C., 2013. Casarett & Doull's Toxicology: The Basic Science of Poisons, eighth edition. McGraw-Hill Education.

Klees, M., Hombrecher, K., Gladtke, D., 2017. Polychlorinated biphenyls in the surrounding of an e-waste recycling facility in North-Rhine Westphalia: levels in plants and dusts, spatial distribution, homologue pattern and source identification using the combination of plants and wind direction data. Sci. Total Environ. 603–604, 606–615.

Krieger, N., 2010. Workers are people too: societal aspects of occupational health disparities—an ecosocial perspective. Am. J. Ind. Med. 53 (2), 104–115.

Kumar, S., Rawat, S., 2015. Future e-waste: standardisation for reliable assessment. Gov. Inf. Q. http://dx.doi.org/10.1016/j.giq.2015.11.006.

Kumar, A., Holuszko, M., Espinosa, D.C.R., 2017. E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recycl. 122, 32–42.

Kumari, A., Jha, M.K., Lee, J.-C., Singh, R.P., 2016. Clean process for recovery of metals and recycling of acid from the leach liquor of PCBs. J. Clean. Prod. 112 (Part 5), 4826–4834.

Labunska, I., Abdallah, M.A.-E., Eulaers, I., Covaci, A., Tao, F., Wang, M., et al., 2015. Human dietary intake of organohalogen contaminants at e-waste recycling sites in Eastern China. Environ. Int. 74, 209–220.

Lebel, S., 2016. Fast machines, slow violence: ICTs, planned obsolescence, and e-waste. Globalizations 13 (3), 300–309.

Lecler, M.T., Zimmermann, F., Silvente, E., Clerc, F., Chollot, A., Grosjean, J., 2015. Exposure to hazardous substances in cathode ray tube (CRT) recycling sites in France. Waste Manag. 39, 226–235.

Leong, F.T.L., Eggerth, D.E., Chang, D., Flynn, M.A., Ford, J.K., Martinez, R.O., 2017. Introduction. In: Leong, F.T.L., Eggerth, D.E., Chang, D., Flynn, M.A., Ford, J.K., Martinez, R.O. (Eds.), Occupational Health Disparities among Racial and Ethnic Minorities: Formulating Research Needs and Directions. American Psychological Association, Washington, D.C..

Lepawsky, J., 2015. The changing geography of global trade in electronic discards: time to rethink the e-waste problem. Geogr. J. 181 (2), 147–159.

Li, J., Zeng, X., Chen, M., Ogunseitan, O.A., Stevels, A., 2015. "Control-alt-delete": rebooting solutions for the E-waste problem. Environ. Sci. Technol. 49 (12), 7095–7108.

Li, J., He, X., Zeng, Xianlai, 2016. Designing and examining e-waste recycling process: methodology and case studies. Environ. Technol. 38 (6), 652–660.

Li, X., Tian, Y., Zhang, Y., Ben, Y., Lv, Q., 2017. Accumulation of polybrominated diphenyl ethers in breast milk of women from an e-waste recycling center in China. J. Environ. Sci. 52, 305–313.

Liang, L., Sharp, A., 2016. Determination of the knowledge of e-waste disposal impacts on the environment among different gender and age groups in China, Laos, and Thailand. Waste Manag. Res. 34 (4), 388–395.

Lin, Y., Xu, X., Dai, Y., Zhang, Y., Li, W., Huo, X., 2016. Considerable decrease of antibody titers against measles, mumps, and rubella in preschool children from an e-waste recycling area. Sci. Total Environ. 573, 760–766.

Lin, X., Xu, X., Zeng, X., Xu, L., Zeng, Z., Huo, X., 2017. Decreased vaccine antibody titers following exposure to multiple metals and metalloids in e-waste-exposed preschool children. Environ. Pollut. 220 (Pt A), 354–363.

Lines, K., Graside, B., Sinha, S., Fedorenko, I., 2016. Clean and Inclusive? Recycling E-waste in China and India. International Institute for Environment and Development. http://pubs.iied.org/pdfs/16611IIED.pdf, Accessed date: 30 May 2017.

Lu, S.Y., Li, Y.X., Zhang, T., Cai, D., Ruan, J.J., Huang, M.Z., et al., 2017. Effect of E-waste recycling on urinary metabolites of organophosphate flame retardants and plasticizers and their association with oxidative stress. Environ. Sci. Technol. 51 (4), 2427–2437.

Lundgren, K., 2012. The Global Impact of E-waste: Addressing the Challenge. International Labour Organization, Geneva, Switzerland. http://ilo.org/sector/Resources/publications/WCMS_196105/lang–en/index.htm, Accessed date: 30 May 2017.

Ma, J., Kannan, K., Cheng, J., Hori, Y., Wu, Q., Wang, W., 2008. Concentrations, profiles, and estimated human exposures for polychlorinated dibenzo-p-dioxins and dibenzofurans from electronic waste recycling facilities and a chemical industrial complex in Eastern China. Environ. Sci. Technol. 42, 8252–8259.

Ma, J., Addink, R., Yun, S., Cheng, J., Wang, W., Kannan, K., 2009. Polybrominated dibenzo-p-dioxins/dibenzofurans and polybrominated diphenyl ethers in soil, vegetation, workshop-floor dust, and electronic shredder residue from an electronic waste recycling facility and in soils from a chemical industrial complex in Eastern China. Environ. Sci. Technol. 43, 7350–7356.

Ma, Z.Q., Jung, Y.H., Chang, T.H., Seo, J.H., Zhang, H., Cai, Z., Gong, S., 2016. Green microwave electronics for the coming era of flexible electronics. In: Proceedings from Microwave Symposium (IMS). IEEE MTT-S International, San Francisco, CA, USA (22–27 May).

Mackintosh, S.A., Wallace, J.S., Gross, M.S., Navarro, D.D., Pérez-Fuentetaja, A., Alaee, M., et al., 2015. Review on the occurrence and profiles of polybrominated diphenyl ethers in the Philippines. Environ. Int. 85, 314–326.

Magalini, F., 2016. Global challenges for e-waste management: the societal implications. Rev. Environ. Health 31 (1), 137–140.

Massari, M., Monzini, P., 2006. Dirty businesses in Italy: a case-study of illegal trafficking in hazardous waste. Global Crime. 6 (3–4), 285–304.

Matsukami, H., Suzuki, G., Tue, N.M., Tuyen, L.H., Viet, P.H., Takahashi, S., et al., 2016. Analysis of monomeric and oligomeric organophosphorus flame retardants in fish muscle tissues using liquid chromatography–electrospray ionization tandem mass spectrometry: application to Nile tilapia (*Oreochromis niloticus*) from an e-waste processing area in northern Vietnam. Emerg. Contam. 2 (2), 89–97.

Matsukami, H., Suzuki, G., Someya, M., Uchida, N., Tue, N.M., Tuyen, L.H., et al., 2017. Concentrations of polybrominated diphenyl ethers and alternative flame retardants in surface soils and river sediments from an electronic waste-processing area in northern Vietnam, 2012–2014. Chemosphere 167, 291–299.

McCann, D., Wittmann, A., 2015. E-waste Prevention, Take-back System Design and Policy Approaches. United Nations University/Step Initiative. http://www.step-initiative.org/news/step-green-paper-explores-policy-solutions-to-e-waste-problem.html, Accessed date: 30 May 2017.

Meyer, D.E., Katz, J.P., 2016. Analyzing the environmental impacts of laptop enclosures using screening-level life cycle assessment to support sustainable consumer electronics. J. Clean. Prod. 112, 369–383.

Milovantseva, N., Fitzpatrick, C., 2016. Effect of Waste Legislation on Transboundary Movements of EEE Destined for Reuse: Impact of E-waste Regulations on Reuse Organizations and Possible Future Direction. United Nations University/Step Initiative. http://www.step-initiative.org/files/step-2014/Publications/Green%20and%20White%20Papers/Step_GP_TBM_draft_fin_16_01_13.pdf, Accessed date: 6 March 2017.

MJC & Associates, 2004. Screening Level Human Health and Ecological Risk Assessment for Generic E-waste Processing Facility: ICT Innovation and Computers for Schools Program. Industry Canada and National Office of Pollution Prevention, Environment Canada, pp. MJC03–126 September 2004.

Mohanty, S., Vermeersch, E., Hintsa, J., Di Cortemiglia, V.L., Liddane, M., 2015. Weaknesses in European e-waste management. In: Proceedings from the Hamburg International Conference of Logistics (HICL), Hamburg, Germany, . https://hicl.org/publications/2015/22/535.pdf, Accessed date: 6 October 2017.

Morris, A., Metternicht, G., 2016. Assessing effectiveness of WEEE management policy in Australia. J. Environ. Manag. 181, 218–230.

Movilla, A.N., Zwolinski, P., Dewulf, J., Mathieux, F., 2016. A method for manual disassembly analysis to support the ecodesign of electronic displays. Res. Conserv. Theatr. Rec. 114, 42–58.

Namias, J., 2013. The Future of Electronic Waste Recycling in the United States: Obstacles and Domestic Solutions. MS thesis. Dept. Earth and Environmental Engineering, Columbia University, New York.

Nartey, K.V., 2016. Environmental and Health Impacts of Informal E-waste Recycling in Agbogbloshie, Accra, Ghana: Recommendations for Sustainable Management. PhD Thesis. Rheinischen Friedrich-Wilhelms-Universität, Bonn, Germany.

NIOSH/ASSE (National Institute for Occupational Safety and Health/American Society for Safety Engineers), 2015. In: Flynn, M.A., Cunningham, T.R., Guerin, R.J., Keller, B., Chapman, L.J., Hudson, D., Salgado, C. (Eds.), Overlapping Vulnerabilities: The Occupational Safety and Health of Young Workers in Small Construction Firms. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH), Cincinnati, OH (Publication No. 2015-178).

O'Connor, M.P., Zinnerman, J.B., Anastas, P.T., Plata, D.L., 2016. A strategy for material supply chain sustainability: enabling a circular economy in the electronics industry through green engineering. ACS Sustain. Chem. Eng. 4 (11), 5879–5888.

Page, E., Ceballos, D., Oza, A., Gong, W., Mueller, C., 2015. Metal Exposures in an Electronic Scrap Recycling Facility. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health Report No. 2013-0067-3228. https://www.cdc.gov/niosh/hhe/reports/pdfs/2013-0067-3228.pdf, Accessed date: 8 June 2017.

Pascale, A., Sosa, A., Bares, C., Battocletti, A., Moll, M.J., Pose, D., et al., 2016. E-waste informal recycling: an emerging source of lead exposure in South America. Ann. Glob. Health 82 (1), 197–201.

Peluola, A., 2016. Investigation of the implementation and effectiveness of electronic waste management in Nigeria. Model. Earth Syst. Environ. 2, 100.

Perkins, D.N., Brune Drisse, M.-N., Nxele, T., Sly, P.D., 2014. E-waste: a global hazard. Ann. Glob. Health 80 (4), 286–295.

Petridis, N.E., Stiakakis, E., Petridis, K., Dey, P., 2016. Estimation of computer waste quantities using forecasting techniques. J. Clean. Prod. 112, 3072–3085.

Pickren, G., 2015. Making connections between global production networks for used goods and the realm of production: a case study on e-waste governance. Glob. Netw. 14 (4), 403–423.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408 (2), 183–191.

Rucevska, I.N.C., Isarin, N., Yang, W., Liu, N., Yu, K., Sandnæs, S., et al., 2015. Waste Crime Waste Risks - Gaps in the Meeting the Global Waste Challenge, A UNEP Rapid Response Assessment. United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal. http://www.unep.org/ourplanet/september-2015/unep-publications/waste-crime-waste-risks-gaps-meeting-global-waste-challenge-rapid, Accessed date: 6 January 2017.

Ryneal, M., 2016. Turning Waste Into Gold: Accumulation by Disposal and the Political Economy of E-waste Urban Mining. PhD thesis. Northern Arizona University, Arizona, USA (ProQuest Number: 10125349).

Sabbaghi, M., Cade, W., Behdad, S., Bisantz, A.M., 2017. The current status of the consumer electronics repair industry in the U.S.: a survey-based study. Resour. Conserv. Recycl. 116, 137–151.

Sahle-Demessie, E., Richardson, T., Changseok Han, C., Dietrich, J., Wang, J., 2016. Characterizing of Emissions From Open Burning of Electronic Waste using TG-GC-MS System. https://resource-recycling.com/e-scrap/wp-content/uploads/sites/2/2017/02/Emissions-from-Open-Burning-of-Electronic-Waste-Application-Note-013098_01-2.pdf, Accessed date: 6 February 2017.

Schluep, M., Hagelueken, C., Kuehr, R., Magalini, F., Maurer, C., Meskers, E., et al., 2009. Recycling From e-Waste to Resources. Sustainable Innovation and Technology Transfer Industrial Sector Studies. UNEP/Step. http://www.unep.org/pdf/Recycling_From_e-waste_to_resources.pdf, Accessed date: 6 February 2017.

Scruggs, C.E., Nimpuno, N., Moore, R.B.B., 2016. Improving information flow on chemicals in electronic products and E-waste to minimize negative consequences for health and the environment. Resour. Conserv. Recycl. 113, 149–164.

Seeberger, J., Grandhi, R., Kim, S.S., Mase, W.A., Reponen, T., Ho, S., Chen, A., 2016. E-waste management in the United States and public health implications. J. Environ. Health 79 (3).

Shen, C., Tanga, X., Cheemaa, S.A., Zhanga, C., Khana, M.I., Lianga, F., et al., 2009. Enhanced phytoremediation potential of polychlorinated biphenyl contaminated soil from e-waste recycling area in the presence of randomly methylated-β-cyclodextrins. J. Hazard. Mater. 172 (2–3), 1671–1676.

Shen, H., Guan, R., Ding, G., Chen, Q., Lou, X., Chen, Z., et al., 2017. Polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs) and polychlorinated biphenyls (PCBs) in Zhejiang foods (2006–2015): market basket and polluted areas. Sci. Total Environ. 574, 120–127.

Shi, J.C., Zheng, G.J.S., Wong, M.H., Liang, H., Li, Y.L., Wu, Y.L., et al., 2016. Health risks of polycyclic aromatic hydrocarbons via fish consumption in Haimen bay (China), downstream of an e-waste recycling site (Guiyu). Environ. Res. 147, 233–240.

Singh, N., Li, J., Zeng, X., 2016. Global responses for recycling waste CRTs in e-waste. Waste Manag. 57, 187–197.

Someya, M., Suzuki, G., Ionas, A.C., Tue, N.M., Xu, F., Matsukami, H., et al., 2016. Occurrence of emerging flame retardants from e-waste recycling activities in the northern part of Vietnam. Emerg. Contam. 2 (2), 58–65.

Son, K.B., Lee, D.S., Lim, S.R., 2015. Effect of technology convergence for tablet PC on potential environmental impacts from heavy metals. Int J Sust Dev World 23 (2), 154–162.

Song, Q., Li, J., 2015. A review on human health consequences of metals exposure to e-waste in China. Environ. Pollut. 196, 450–461.

Song, Q., Zeng, X., Li, J., Duan, H., Yuan, W., 2015. Environmental risk assessment of CRT and PCB workshops in a mobile e-waste recycling plant. Environ. Sci. Pollut. Res. 22 (16), 12366–12373.

Srigboh, R.K., Basu, N., Stephens, J., Asampong, E., Perkins, M., Neitzel, R.L., Fobil, J., 2016. Multiple elemental exposures amongst workers at the Agbogbloshie electronic waste (e-waste) site in Ghana. Chemosphere 164, 68–74.

Step, 2014. One Global Definition of E-waste. Solving the E-Waste Problem (Step) White Paper Series. United Nations University/Step Initiative 2014. http://www.step-initiative.org/files/step/_documents/StEP_WP_One%20Global%20Definition%20of%20E-waste_20140603_amended.pdf, Accessed date: 8 June 2017.

Step, 2016. Guiding Principles to Develop E-waste Management Systems and Legislation. Solving the E-Waste Problem (Step) White Paper Series. United Nations University/Step Initiative 2016. http://www.step-initiative.org/files/step-2014/Publications/Green%20and%20White%20Papers/Step_WP_WEEE%20systems%20and%20legislation_final.pdf, Accessed date: 30 May 2017.

Sthiannopkao, S., Wong, M.H., 2013. Handling e-waste in developed and developing countries: initiatives, practices, and consequences. Sci. Total Environ. 463–464, 1147–1153.

Sugimura, Y., Murakami, S., 2016. Problems in Japan's governance system related to end-of-life electrical and electronic equipment trade. Resour. Conserv. Recycl. 112, 93–106.

Suzuki, G., Someya, M., Matsukami, H., Tue, N.M., Uchida, N., Tuyen, L.H., et al., 2016. Comprehensive evaluation of dioxins and dioxin-like compounds in surface soils and river sediments from e-waste-processing sites in a village in northern Vietnam: heading towards the environmentally sound management of e-waste. Emerg. Contam. 2 (2), 98–108.

Szałatkiewicz, J., 2014. Metals content in printed circuit board waste. Pol. J. Environ. Stud. 23 (6), 2365–2369.

Tansel, B., 2017. From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35–45.

Tao, F., Matsukami, H., Suzuki, G., Nguyen Minh, T., Pham Hung, V., Takigami, H., Harrad, S., 2016. Emerging halogenated flame retardants and hexabromocyclododecanes in food samples from an e-waste processing area in Vietnam. Environ. Sci.: Processes Impacts 18, 361–370.

Terazono, A., Oguchi, M., Yoshida, A., Medina, R.P., Ballesteros Jr., F.C., 2017. Material recovery and environmental impact by informal e-waste recycling site in the Philippines. In: Matsumoto (Ed.), Sustainability through Innovation in Product Life Cycle Design. vol. Part II. Springer Singapore, Singapore, pp. 197–213.

Toxnet (n.d.). Toxicology Data Network. https://toxnet.nlm.nih.gov/ (accessed 30.05. 2017).

Tran, H.P., Wang, F., Dewel, J., Huynh, T.H., Schaubroeck, T., 2016. Estimation of the unregistered inflow of electrical and electronic equipment to a domestic market: a case study on televisions in Vietnam. Environ. Sci. Technol. 50, 2424–2433.

Tue, N.M., Goto, A., Takahashi, S., Itai, T., Asante, K.A., Nomiyama, K., et al., 2016a. Soil contamination by halogenated polycyclic aromatic hydrocarbons from open burning of e-waste in Agbogbloshie (Accra, Ghana). J. Mater. Cycles Waste Manage. 19 (4), 1324–1332.

Tue, N.M., Goto, A., Takahashi, S., Itai, T., Asante, K.A., Kunisue, T., Tanabe, S., 2016b. Release of chlorinated, brominated and mixed halogenated dioxin-related compounds to soils from open burning of e-waste in Agbogbloshie (Accra, Ghana). J. Hazard. Mater. 302, 151–157.

UNEP (United Nations Environment Programme), 2010. Introductory Note to the Basel Convention by Dr. Katharina Kummer Peiry, Executive Secretary of the Basel Convention. UNEP. http://legal.un.org/avl/ha/bcctmhwd/bcctmhwd.html, Accessed date: 15 June 2017.

US DOJ (United States Department of Justice), 2010. A Review of Federal Prison Industries' Electronic-Waste Recycling Program. Office of the Inspector General, Oversight and Review Division; October 2010.

US EPA, 2016a. EPD Will Not Tolerate Illegal Import Of Hazardous E-Waste, Press Release, June 17, 2016. http://www.info.gov.hk/gia/general/201606/17/P201606171114.htm, Accessed date: 15 June 2017.

US EPA, 2016b. Implementation Study of the Electronics Recycling Standards: R2 and e-Stewards®. United States Environmental Protection Agency, Office of Resource Conservation and Recovery and Abt Associates, Inc.

US EPA (United States Environmental Protection Agency), 2015. Flame Retardants in Printed Circuit Boards. Chapter 3. Final Report. EPA Publication 744-R-15-001. https://www.epa.gov/sites/production/files/2015-08/documents/pcb_final_report.pdf, Accessed date: 15 June 2017.

Verdecchia, R., Ricchiuti, F., Hankel, A., Lago, P., Procaccianti, G., 2017. Green ICT research and challenges. In: Wohlgemuth, V., Fuchs-Kittowski, F., Wittmann, J. (Eds.), Advances and New Trends in Environmental Informatics: Stability, Continuity, Innovation. Springer International Publishing, Cham, pp. 37–48.

Wang, Yan, Luo, C., Wang, S., Cheng, Z., Li, J., Gan, Z., 2016. The abandoned e-waste recycling site continued to act as a significant source of polychlorinated biphenyls: an in situ assessment using fugacity samplers. Environ. Sci. Technol. 50, 8623–8630.

Wang, Yalin, Hu, J., Lin, W., Wang, N., Li, C., Luo, et al., 2016. Health risk assessment of migrant workers' exposure to polychlorinated biphenyls in air and dust in an e-waste recycling area in China: indication for a new wealth gap in environmental rights. Environ. Int. 87, 33–41.

Wang, Zhaohua, Zhang, B., Guan, D., 2016. Take responsibility for electronic waste disposal. Nature 536 (7614), 23–25.

Wang, Yan, Wu, X., Hou, M., Zhao, H., Chen, R., Luo, C., Zhang, G., 2017. Factors influencing the atmospheric concentrations of PCBs at an abandoned e-waste recycling site in South China. Sci. Total Environ. 578, 34–39.

WDE (Washington State Department of Ecology), 2016. Electronics Recycler Fined $444,000 for Illegally Disposing of Dangerous Waste Overseas, 1 September 2016. http://www.ecy.wa.gov/news/2016/114.html, Accessed date: 30 May 2017.

Wilson, D.C., Rodic, L., Modak, P., Soos, R., Carpintero Rogero, A., Velis, C., et al., 2015. Global Waste Management Outlook. UNEP. http://www.unep.org/ourplanet/september-2015/unep-publications/global-waste-management-outlook, Accessed date: 30 May 2017.

Wilson, G.T., Smalley, G., Suckling, J.R., Lilley, D., Lee, J., Mawle, R., 2017. The hibernating mobile phone: dead storage as a barrier to efficient electronic waste recovery. Waste Manag. 60, 521–533.

Wittsiepe, J., Fobil, J.N., Till, H., Burchard, G.-D., Wilhelm, M., Feldt, T., 2015. Levels of polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/Fs) and biphenyls (PCBs) in blood of informal e-waste recycling workers from Agbogbloshie, Ghana, and controls. Environ. Int. 79, 65–73.

Woo, S.H., Lee, D.S., Lim, S.R., 2016. Potential resource and toxicity impacts from metals in waste electronic devices. Integr. Environ. Assess. Manag. 12 (2), 364–370.

Wu, Q., Leung, J.Y.S., Geng, X., Chen, S., Huang, X., Li, H., et al., 2015. Heavy metal contamination of soil and water in the vicinity of an abandoned e-waste recycling site: implications for dissemination of heavy metals. Sci. Total Environ. 506–507, 217–225.

Wu, Chen-Chou, Bao, L.-J., Tao, S., Zeng, E.Y., 2016. Dermal uptake from airborne organics as an important route of human exposure to e-waste combustion fumes. Environ. Sci. Technol. 50 (13), 6599–6605.

Wu, Ping-Fan, Yu, L.L., Li, L., Zhang, Y., Li, X.H., 2016. Maternal transfer of dechloranes and their distribution among tissues in contaminated ducks. Chemosphere 150, 514–519.

Xiao, X., Hu, J., Peng, P.a., Chen, D., Bi, X., 2016. Characterization of polybrominated dibenzo-p-dioxins and dibenzo-furans (PBDDs/Fs) in environmental matrices from an intensive electronic waste recycling site, South China. Environ. Pollut. 212, 464–471.

Xu, Long, Huo, X., Zhang, Y., Li, W., Zhang, J., Xu, X., 2015. Polybrominated diphenyl ethers in human placenta associated with neonatal physiological development at a typical e-waste recycling area in China. Environ. Pollut. 196, 414–422.

Xu, Xinjin, Zeng, X., Boezen, H.M., Huo, X., 2015. E-waste environmental contamination and harm to public health in China. Front. Med-PRC. 9 (2), 220–228.

Xu, Long, Ge, J., Huo, X., Zhang, Y., Lau, A.T.Y., Xu, X., 2016. Differential proteomic expression of human placenta and fetal development following e-waste lead and cadmium exposure in utero. Sci. Total Environ. 550, 1163–1170.

Xu, Pengjun, Tao, B., Ye, Z., Zhao, H., Ren, Y., Zhang, T., et al., 2016. Polycyclic aromatic hydrocarbon concentrations, compositions, sources, and associated carcinogenic risks to humans in farmland soils and riverine sediments from Guiyu, China. J. Environ. Sci. 48, 102–111.

Yadav, V., Cheraghi, S.A., Namboodiri, V., 2015. The OS elixir: on the impact of operating system upgrades on mobile device lifespan. In: Proceeding From Green Computing Conference and Sustainable Computing Conference (IGSC), 2015 Sixth International, Las Vegas, NV, USA, (14–16 December).

You, Z.W., Hou, W.J., Wang, X.C., Ma, J.S., Liu, J., 2016. Design strategies for developing sustainable consumer electronics. J. Residual. Sci. Tech. 13, S219–S226.

Yuan, B., Fu, J., Wang, Y., Jiang, G., 2017. Short-chain chlorinated paraffins in soil, paddy seeds (*Oryza sativa*) and snails (Ampullariidae) in an e-waste dismantling area in China: homologue group pattern, spatial distribution and risk assessment. Environ.

Pollut. 220 (Pt A), 608–615.

Zeng, Xiang, Xu, X., Boezen, H.M., Huo, X., 2016. Children with health impairments by heavy metals in an e-waste recycling area. Chemosphere 148, 408–415.

Zeng, Xianlai, Gong, R., Chen, W.Q., Jinhui, l., 2016. Uncovering the recycling potential of "new" WEEE in China. Environ. Sci. Technol. 50, 1347– – 1358.

Zeng, X., Yang, C., Chiang, J.F., Li, J., 2017. Innovating e-waste management: from macroscopic to microscopic scales. Sci. Total Environ. 575, 1–5.

Zhang, L., Xu, Z., 2016. A review of current progress of recycling technologies for metals from waste electrical and electronic equipment. J. Clean. Prod. 127, 19–36.

Zhang, T., Xue, J., Gao, C.Z., Qiu, R.L., Li, Y.X., Li, X., et al., 2016. Urinary concentrations of bisphenols and their association with biomarkers of oxidative stress in people living near e-waste recycling facilities in China. Environ. Sci. Technol. 50 (7), 4045–4053.

Zhao, Y., Ma, J., Qiu, X., Lin, Y., Yang, Q., Zhu, T., 2013. Gridded field observations of polybrominated diphenyl ethers and decabromodiphenyl ethane in the atmosphere of North China. Environ. Sci. Technol. 47 (15), 8123–8129.

Zheng, X., Xu, F., Chen, K., Zeng, Y., Luo, X., Chen, S., et al., 2015. Flame retardants and organochlorines in indoor dust from several e-waste recycling sites in South China: composition variations and implications for human exposure. Environ. Int. 78, 1–7.

Zheng, Xiaobo, Xu, F., Luo, X., Mai, B., Covaci, A., 2016. Phosphate flame retardants and novel brominated flame retardants in home-produced eggs from an e-waste recycling region in China. Chemosphere 150, 545–550.

Zheng, Jing, Yu, L.H., Chen, S.J., Hu, G.C., Chen, K.H., Yan, X., et al., 2016. Polychlorinated biphenyls (PCBs) in human hair and serum from e-waste recycling workers in Southern China: concentrations, chiral signatures, correlations, and source identification. Environ. Sci. Technol. 50 (3), 1579–1586.

Zheng, Xiangbin, Xu, X., Yekeen, T.A., Zhang, Y., Chen, A., Kim, S.S., et al., 2016. Ambient air heavy metals in PM 2.5 and potential human health risk assessment in an informal electronic-waste recycling site of China. Aerosol Air Qual. Res. 16, 388–397.

Zhu, C., Wang, P., Li, Y., Chen, Z., Li, H., Ssebugere, P., Zhang, Q., Jiang, Q., 2017. Trophic transfer of hexabromocyclododecane in the terrestrial and aquatic food webs from an e-waste dismantling region in East China. Environ. Sci.: Processes Impacts 19 (2), 154–160.