E-Waste: A Global Hazard

Devin N. Perkins, BS, Marie-Noel Brune Drisse, MS, Tapiwa Nxele, MS, and Peter D. Sly, MD

ABSTRACT

Background: Waste from end-of-life electrical and electronic equipment, known as e-waste, is a rapidly growing global problem. E-waste contains valuable materials that have an economic value when recycled. Unfortunately, the majority of e-waste is recycled in the unregulated informal sector and results in significant risk for toxic exposures to the recyclers, who are frequently women and children.

Objectives: The aim of this study was to document the extent of the problems associated with inappropriate e-waste recycling practices.

Methods: This was a narrative review that highlighted where e-waste is generated, where it is recycled, the range of adverse environmental exposures, the range of adverse health consequences, and the policy frameworks that are intended to protect vulnerable populations from inappropriate e-waste recycling practices.

Findings: The amount of e-waste being generated is increasing rapidly and is compounded by both illegal exportation and inappropriate donation of electronic equipment, especially computers, from developed to developing countries. As little as 25% of e-waste is recycled in formal recycling centers with adequate worker protection. The health consequences of both direct exposures during recycling and indirect exposures through environmental contamination are potentially severe but poorly studied. Policy frameworks aimed at protecting vulnerable populations exist but are not effectively applied.

Conclusions: E-waste recycling is necessary but it should be conducted in a safe and standardized manor. The acceptable risk thresholds for hazardous, secondary e-waste substances should not be different for developing and developed countries. However, the acceptable thresholds should be different for children and adults given the physical differences and pronounced vulnerabilities of children. Improving occupational conditions for all e-waste workers and striving for the eradication of child labor is non-negotiable.

Key Words: children's environmental health, developmental toxicology, electronic waste, e-waste, heavy metals

INTRODUCTION

The adverse consequences for health and the ecology of exposure to waste products from human consumption have long been recognized. A relatively recently recognized hazardous waste product comes from discarded electrical and electronic equipment (EEE).[1] Such products contain costly components that have economic value if recycled. However, EEE also contains potentially hazardous substances that may be directly released or generated during the recycling process, generating what is known as e-waste. The creation and release of hazardous byproducts often occurs in the so-called "informal" sector of e-waste recycling where modern industrial processes are not used and where worker protection often is inadequate. Unprotected exposure to e-waste is not advisable for any individual. Of exposed groups, children are particularly vulnerable to many of the components in e-waste. In this article, we will review the scope of the problem associated with discarded EEE and component recycling, outline the regulatory approaches to minimize adverse health effects, and highlight current areas for improvement.

The Scope of the Problem: Defining, Quantifying, and Tracking E-waste

EEE includes items that have either a battery or a power cord. E-waste generated from discarded EEE is commonly divided into 3 main categories: large household appliances (refrigerators and washing machines), information technology (IT) and telecom (personal computers, monitors, and laptops), and consumer equipment (TVs, DVD players, mobile phones, mp3 players, and leisure and sporting equipment).[2] Equipment components including batteries, circuit boards, plastic casings, cathode-ray tubes,

From the Department of Public Health, Environmental and Social Determinants of Health, World Health Organization, Geneva, Switzerland (DNP, M-NBD, TN); World Health Organization Collaborating Centre for Children's Health and Environment, Queensland Children's Medical Research Institute, The University of Queensland, Brisbane, Australia (PDS). Address correspondence to P. D. Sly.; e-mail: p.sly@uq.edu.au

The authors declare that they have no conflicts of interest. Staff members of WHO are responsible for the views expressed in this publication, which do not necessarily represent the decisions, policy, or views of WHO.

http://dx.doi.org/10.1016/j.aogh.2014.10.001

activated glass, and lead capacitors also are considered to be e-waste.[2] There are varying estimates as to the amount of domestic, regional, and global e-waste produced. According to StEP (Solving the E-waste Problem Initiative), the 2012 global generation of e-waste totaled 45.6 million metric tons.[3] The United Nations Environmental Program (UNEP) approximated that the amount of e-waste produced in 2012 is enough to fill 100 Empire State buildings and averages to more than 6.8 kg (15 lb) for every living person. The global population is nearly 7 billion but although there are only 4.5 billion toilets worldwide, there are estimated to be at least 6 billion mobile phones.[2,4] In 2012 alone, China reportedly generated 11.1 million tons of e-waste and the United States produced 10 million tons.[5] This means that, on average, each American generates 29.5 kg of e-waste compared with the less than 5 kg per person in China. These numbers likely underestimate the actual total amounts of e-waste.

The sheer volume of e-waste is problematic, but more concerning is the rapid increase of this complex, global waste stream. E-waste is one of, if not the, fastest growing source of waste worldwide.[1,3,6,7] The 2012 UN report projected that by 2017 global e-waste will increase a further 33% from 49.7 million to 65.4 million tons per annum.[8] E-waste from cell phones in India alone is expected to increase 18-fold by 2020.[3,9] The total amount of e-waste produced is exponentially increasing because of multiple factors. Consumer demand and a high obsolescence rate lead to frequent and unnecessary purchases of EEE.[10] For example, new cell phone models are released at highly regular intervals. Not only do cell phone models evolve, but the accessories, such as chargers, often change with each new model. Short innovation cycles and low recycling rates contribute to rapidly rising quantities of e-waste. The acceptable consumer life span of EEE has been dropping, causing significant additions to e-waste. The average life span of computers has reportedly dropped in recent years by 50% from 4 to 2 years.[3,11] Computers and cell phones are used for a wide variety purposes, including educational campaigns where a laptop is provided to each student. Computer access and skills are valuable to education but such initiatives also have the unintended consequence of adding to the global burden of e-waste.

E-waste is a global, interregional, and domestic problem. Of the 20 million to 50 million tons generated yearly, it is estimated that 75% to 80% is shipped to countries in Asia and Africa for "recycling" and disposal.[12] Loopholes in current e-waste regulations allow for the export of e-waste from developed to developing countries under the guise of "donation" and "recycling" purposes. The Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (The Basel Convention),[13] launched The Partnership for Action on Computing Equipment (PACE) to facilitate environmentally sound management of used and end-of-life computing equipment. Among other tasks, PACE has provided guidelines on what functionality computers and computer components, including batteries, should have to be considered usable computers and, as such, suitable for donation.[14] According to PACE, a charitable donation is the "transfer of computing equipment or its components, that are not waste, for their intended direct reuse for purposes of charity without any monetary rewards or benefits, or for barter."[13,15] The UNEP Guidelines on Environmentally Sound Testing, Refurbishment and Repair of Used Computing Equipment provide a set of principles for donations of functioning used computing equipment. These principles are to:

1. provide a useful product;
2. provide an appropriate product;
3. ensure and verify availability of technical support in recipient community;
4. test, certify and label functionality;
5. ensure availably of training in recipient community;
6. ensure full transparency, contract, notification, and consent prior to delivery; and
7. export in accordance with applicable national and international controls.[15]

If followed as closely as possible, these principles could drastically minimize the amount of end-of-life computing equipment that is mislabeled and exported as donated "functional used computing equipment" that is really waste.[15]

Distinguishing between types of e-waste is essential. The Basel Convention technical guidelines on transboundary movements of e-waste and used EEE differentiate waste streams based on functionality and the need or potential for repair (Table 1).[16] To test the functionality of used EEE, specifically computing equipment, one can conduct a Power on Self Test (POST).[15]

The final destination of nearly 70% of e-waste is either unreported or unknown.[17] Approximately 25% (2.1 million tons) of the estimated 8.7 million tons of e-waste produced in the European Union (EU) each year is collected and recycled in formal processing plants where workers are protected by modern industrial standards. The remaining 75% is added to the "hidden flow" of untraced and unreported e-waste.[10] The European Environment Agency estimates that up to 1.3 million tons of discarded EEE are exported from the EU annually mostly to Africa and Asia.[6] In 2005, 18 European seaports were inspected and 47% of waste bound for export was not being exported legally. In 2003, 23,000 metric tons of undeclared e-waste from the United Kingdom was illegally exported to India, Africa, and Asia.[18] Eighty percent of e-waste generated in the United States reportedly contributes to the global "hidden flow" of e-waste; it is not registered meaning it is either unofficially exported, dumped into landfills, or incinerated.[19] The 20% of e-waste generated in the United States that is formally recycled includes the "official" export of e-waste

Table 1. Classifying the Multiple Types of E-waste

Type of Stream	Description	Classification
New and functioning EEE	New products or components being delivered and shipped between different countries.	This stream is classified as "non-waste" by default (new products for distribution).
Used and functioning EEE suitable for direct reuse	The equipment needs no further repair, refurbishment, or hardware upgrading.	This stream can be classified as "non-waste"; however, in some countries export/import restrictions apply.
Used and nonfunctioning but repairable EEE	Equipment that can be repaired, returning it to a working condition performing the essential functions it was designed for. Testing is required to determine this condition.	Classification of this stream is under discussion by Basel Parties, as the repair process may result in hazardous parts being removed in the country of repair, thus possibly resulting in transboundary movement of hazardous waste. Some countries would classify this stream as "waste"; others classify it as "non-waste."
Used and nonfunctioning and nonrepairable EEE	The common form of "e-waste." Can be mislabeled as "used EEE."	Should be classified as "waste."
WEEE	EEE that is waste within the meaning of the Waste Framework Directive context, including components and subassemblies.	Should be classified as "waste."

EEE, electrical and electronic equipment; WEEE, waste electrical and electronic equipment.
(Adapted ref 16)

to India and China.[19] Official e-waste exports from the United States encompass donated, and often defunct, EEE.[10]

The practice of developed countries exporting e-waste to developing countries has become commonplace for a variety of reasons. High labor costs and stringent environmental regulations for hazardous waste disposal in developed countries encourage the exportation of e-waste to less developed and less regulated countries. Importing e-waste for recycling may provide some short-term economic benefits. However, many developing countries lack the technology, facilities, and resources needed to properly recycle and dispose of e-waste.[10] Recyclers in developing countries that receive e-waste from other countries frequently rely on rudimentary techniques to extract valuable materials from e-waste.[10] E-waste is physically dismantled by using tools such as hammers, chisels, and screw drivers.[20] Printed circuit boards are heated and components are removed.[20] Gold and other metals are recovered from the stripping of metals in open-pit acid baths.[20] Plastics are chipped and melted without necessary and protective ventilation.[20] Burning electrical cables, often in open pits and at relatively low temperatures, to retrieve copper is one of the most common crude recycling practices. Such primitive techniques may appear efficient to the untrained and less equipped recyclers, but they do not ensure environmental protection or occupational safety. In fact, these rudimentary methods may lead to the recovery of materials that are only worth a fraction of the total potential economic return. When developed countries export e-waste for recycling, the opportunity to establish more safe, clean, and efficient techniques is lost.

Sources of Exposure

E-waste recycling can lead to direct or indirect exposure to a variety of hazardous substances that are contained in EEE or formed and released by unsafe recycling practices (Fig. 1). Direct exposure entails skin contact with harmful substances, the inhalation of fine and coarse particles, and the ingestion of contaminated dust. Individuals who directly engage in e-waste recycling with poor protection incur high levels of direct, occupational exposure.[3,21,22] Unsafe recycling techniques used to regain valuable materials often increase the risk for hazardous exposures. There often is a lack of suitable off-gas treatment during such recycling processes, particularly smelting.

Plastics are burned, often at low temperatures, to either dispose of computer casings or to retrieve metals from electronic chips and other components. Incineration releases heavy metals such as lead, cadmium, and mercury.[3,21,23] The toxic fumes released by these techniques often contain polyhalogenated dioxins and furans generated by incomplete combustion at low termperatures.[3,18,23] Polystyrene form, rubber, tires, crop residue, or biomass may be used as fuel for these fires and can cause harmful exposures, independent of the burning

Persistant organic pollutants	Component of electrical and electornic	Ecological source of exposure	Route of exposure
Brominated flame retardants Polybrominated diphenyl ethers (PBDEs) Polybrominated biphenyls (PBBs)	Flame retardants for electronic equipment	Air, dust, food, water, and soil	Ingestion, inhalation, and transplacental
Polychlorinated biphenyls (PCBs)	Dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Air, dust, soil, and food (bio-accumulative in fish and seafood)	Ingestion, inhalation or dermal contact, and transplacental
Dioxins			
Polychlorinated dibenzodioxins (PCDDs) and dibenzofurans (PCDFs)	Released as combustion byproduct	Air, dust, soil, food, water, and vapour	Ingestion, inhalation, dermal contact, and transplacental
Dioxin-like polychlorinated biphenyls	Released as a combustion byproduct but also found in dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Released as combustion byproduct, air, dust, soil, and food (bioaccumulative in fish and seafood)	ngestion, inhalation, and dermal absorption
Polyaromatic hydrocarbons (PAHs)	Released as combustion byproduct	Released as combustion byproduct, air, dust, soil, and food	Ingestion, inhalation, and dermal contact
Elements			
Lead (Pb)	Printed circuit boards, cathode ray tubes (CRTs), light bulbs, televisions, solder, and batteries	Air, dust, water, and soil	Inhalation, ingestion, and dermal contact
Chromium (Cr) or hexavalent chromium	Anticorrosion coatings, data tapes, and floppy disks	Air, dust, water, and soil	Inhalation and ingestion
Cadmium (Cd)	Switches, springs, connectors, printed circuit boards, batteries, infrared detectors, semi-conductor chips, ink or toner photocopying machines, cathode ray tubes, and mobile phones	Air, dust, soil, water, and food (especially rice and vegetables)	Inhalation and ingestion
Mercury (Hg)	Thermostats, sensors, monitors, cells, printed circuit boards, cold cathode fluorescent lamps, and liquid crystal display (LCD) backlights	Air, vapour, water, soil, and food (bioaccumulative in fish)	Inhalation, ingestion, and dermal contact
Zinc (Zn)	Cathode ray tubes and metal coatings	Air, water, and soil	Ingestion and inhalation
Nickel (Ni)	Batteries	Air, soil, water, and food (plants)	Inhalation, ingestion, dermal contact, and transplacental
Lithium (Li)	Batteries	Air, soil, water, and food (plants)	Inhalation, ingestion, and dermal contact
Barium (Ba)	Cathode ray tubesmand fluorescent lamps	Air, soil, water, and food	Ingestion, inhalation and dermal contact
Berylium (Be)	Power supply boxes, computers, x-ray machines, ceramic components of electronics	Air, food, and water	Inhalation, ingestion, and transplacental

(Adapted from ref. 23.)

Figure 1. Potential Hazardous E-waste Exposures

e-waste. Additionally, the working materials used in rudimentary recycling can be injurious.[3] Working materials include cleaning solvents and reagents such as cyanide and other strong leaching acids. Acid leaching can lead to direct contact with liquid acid and the inhalation of acid fumes.[24] "De-soldering" of circuit boards to recover rare and precious metals can release lead-saturated fumes. The combination of toxic byproducts, working materials, and the actual e-waste may lead to adverse health outcomes.

Environmental contamination that is the result of improper e-waste recycling can lead to indirect exposures through contamination of soil, air, and water around e-waste recycling sites. Water contamination has been documented in areas surrounding e-recycling towns in China; metal-contaminated sediments and elevated levels of dissolved metals have been reported in rivers in and around the e-waste recycling town of Guiyu.[3,25,26] The release of hazardous chemicals into the environment can lead to bioaccumulation, food contamination, and widespread ecological exposure.[3,21,22] Children may be exposed in schools, playgrounds, or homes that are near an e-waste recycling site. Concern surrounding transplacental and breast milk exposure is high, although no direct data on the levels of exposure exists.[3,21,22,27] Environmental contamination and resulting ecological exposure requires intensive research not only because hazardous e-waste recycling materials have the ability to spread far distances but they also possess high environmental persistence capabilities. With longer half-lives, these substances have the ability to remain in the environment for extended periods.[28] Ecological exposure may have long-term and widespread health risks.[3,23,29]

An additional source of indirect exposure to toxicants resulting from improper e-waste recycling processes is "take-home exposure."[3] This exposure pathway refers to secondhand exposure to hazardous substances incurred, especially by children, when the substance is brought into the home on clothing, materials, or other objects that have been contaminated with harmful residue from e-waste recycling.[30] Take-home exposure has the capacity to cause low-level, chronic, and long-term exposure.

E-waste Recycling: Formal and Informal Sectors

The final destination of discarded EEE is frequently not in the same country or even on the same continent where the equipment was purchased or used. Exportation of e-waste from developed to developing countries is common. It is estimated that 23% of e-waste generated in developed countries is exported to 7 developing countries.[31] E-waste recycling can be designated as part of the "formal" or "informal" economic sector. Formal e-waste recycling entails specially constructed facilities with proper equipment that allow for the safe extraction of the salvageable materials. These facilities, for the most part, ensure safe working conditions. Not surprisingly, these facilities are expensive to build and run so they rarely exist in less developed countries. Due to variable safety standards, some workers in these facilities may still be at risk for low-dose exposures.[9] Despite proper construction and technique, the surrounding communities may still be at risk for environmental contamination and exposure.[25,26,32,33] "Informal" e-waste recycling is typically characterized as being beyond the reach of official governance, unregulated, lacking structure, unregistered, and illegal.[20]

Developed countries sometimes export older EEE as donations to developing countries. These electronics often die sooner rather than later only increasing the total burden of waste in the "donation"-receiving countries.[34] The demand for imported foreign e-waste has increased as under- or unemployed populations have discovered the potential economic gains from recycling e-waste. The demand in Asia for e-waste heightened when scrap yards found they could extract copper, iron, silicon, nickel, and gold. A mobile phone is 19% copper and 8% iron.[18] Countries where formal e-waste recycling has been recorded include China,[3,23] India, Vietnam,[35] Pakistan, Malaysia, the Philippines, Singapore, Sri Lanka, Thailand,[6] and Kenya.[36]

Official e-waste recycling facilities should conduct environmentally sound management (ESM).[15] ESM is defined as "taking all practicable steps to ensure that used and/or end-of-life products and wastes are managed in a manner which will protect human health and the environment."[15] There are 7 designated ESM criteria:

1. top management commitment to a systematic approach;
2. risk assessment;
3. risk prevention and minimization;
4. legal requirements;
5. awareness, competency, and performance measurement;
6. corrective action; and
7. transparency and verification.[15]

Facilities and recyclers should strive to refurbish and reuse discarded EEE. Dismantling and extracting valuable materials should occur only if reuse is not possible. Within the e-waste recycling facility there are suggested steps to ensure safe refurbishment or disposal (Fig. 2). Facilities in the Organization for Economic Cooperation and Development (OECD)-member countries should follow recommendations from the OECD.[15,37]

Some companies offer free take-back services for old electrical and electronic products. In China, for example, Nokia and Lenovo were among the first companies to do so.[20] Despite the lack of a formal e-waste recycling network in China, there are multiple certified e-waste treatment plans in many of the major cities including 2 in Beijing, 6 in Tianjin, 7 in Shanghai, 4 in Suzhou, 1 in Huizhou, and 1 in Harbin.[20] There are 2 e-waste recycling sites in China that have been subject to a number of a studies on the potential hazards of e-waste recycling: Guiyu in Guangdong province and Taizhou region in Zhejiang province.[3,21,38-41] These towns typify e-waste recycling sites in China. Guiyu has around 150,000 inhabitants and 80% of families are involved in e-waste recycling.[21] E-waste recycling reportedly began in Guiyu in the late 1980s. Laqiao is a town of 400,000 people in Taizhou and is the main e-waste recycling site. At least 10% of the population in Laqiao participates in e-waste recycling which first started in the 1970s.[3,21] There are also e-waste recycling sites in Bengaluru and Delhi, India.[22] West Africa has e-waste recycling sites in Nigeria (Lagos) and Ghana (Accra, Agbogbloshie).[3,6,29]

The informal sector of e-waste recycling is well supplied, mostly unregulated, and largely unknown. Tracking the "hidden flow" of global e-waste is difficult and costly. Informal e-waste recycling often is conducted by people with little to no protective equipment or technology.[25,26] Informal e-waste recycling is often home-based and family-run.[15] Individuals, families, and communities that dismantle e-waste often have made the choice of poison over poverty.[42]

Some e-waste workers are not fully, if at all, aware of the potential health risks involved with e-waste recycling. Among some communities, e-waste recycling is considered more desirable than scavenging through nonelectronic waste. Much of the informal e-waste recycling done in scrap yards and homes is done by children. E-waste is informally processed in many countries, but a high-volume of informal e-waste recycling has been reported in China, Ghana, Nigeria, India, Thailand, the Philippines, and Vietnam.[43] China and India are among the countries where the largest amounts of e-waste is informally processed.[6,29] In India, an estimated 25,000 workers are employed at unregulated e-waste scrap yards in Delhi alone, where 10,000 to 20,000 tons of e-waste is processed annually. The informal sector thrives under slack environmental regulation, high demand for second-hand EEE, and home collection of used EEE by individual recyclers. Some countries, such as China, do not have a municipal e-waste collection network system in place.[20] This absence creates opportunities for home-based e-waste collection and recycling. The informal and formal sectors of e-waste recycling are interdependent. Not only is informal e-waste recycling likely hazardous for human health and the environment, but it also leads to supply deficiencies in the formal sector.[20] Currently, e-waste scavenging provides a source of livelihood, albeit a risky one, to large numbers of people in developing countries.[13,44]

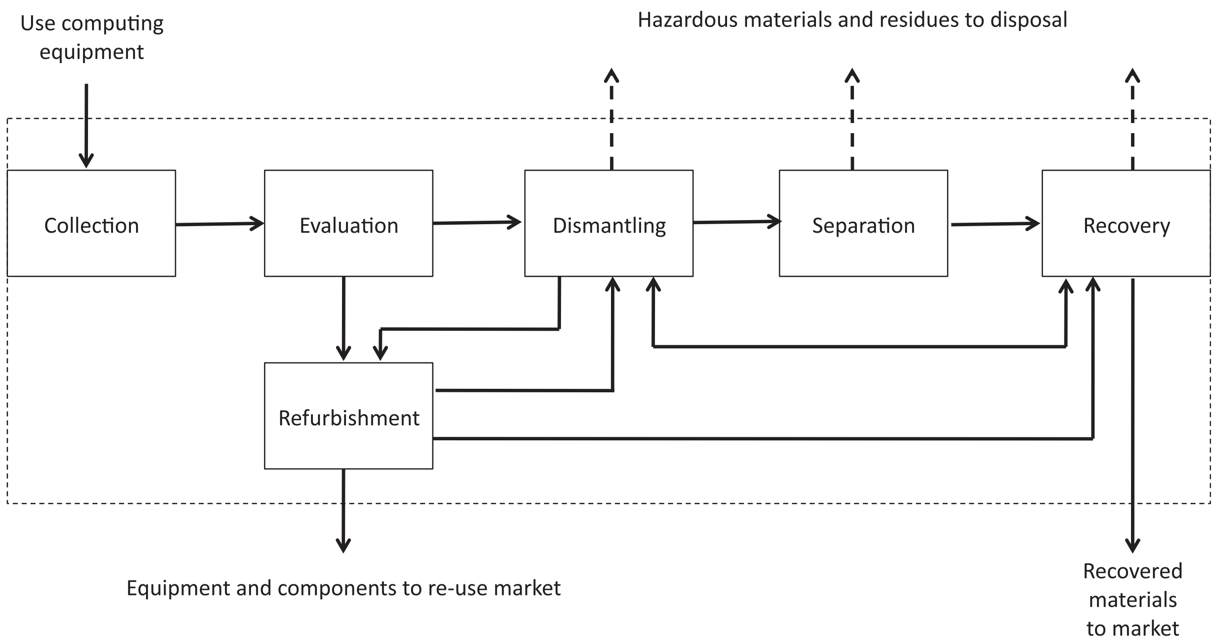

Figure 2. Desired flow diagram for ESM of used EEE within a recycling facility. Abbreviations: EEE, electrical and electronic equipment; ESM, environmentally sound management. (Adapted from ref 15.)

Vulnerable Populations

Marginalized populations bear a disproportionate amount of the negative effects of improper e-waste practices. Most e-waste recyclers, in either the formal or informal sector, are poor and less educated than the respective population average.[12,44] E-waste recycling provides a source of income for people who have few other economic opportunities. E-waste recycling, especially in the informal sector, is geared toward high throughput and output. Occupational safety and environmental protection are not prioritized. Poor children and women, especially those living in urban areas, represent a large portion of e-waste recyclers.[20] Due to the gaps in data, particularly in the informal sector, the total number of children exposed to occupational health and safety risks from e-waste is difficult to estimate.[3,6] However, the International Labor Organization has reported that e-waste workers are often children.[6,12,42,44] Children are considered ideal e-waste workers because they have small, dexterous hands that help them easily dismantle discarded EEE.

The exploitation of children within the e-waste recycling industry is especially concerning given the physiological attributes that contribute to a child's vulnerability. Exposures to hazardous substances, such as polychlorinated biphenyls and dioxins, at e-waste sites are higher for children than for adults. Children are still growing so their intake of water, food, and air in proportion to their height and weight is significantly higher compared to the intake of adults.[3,45] Children also have a much larger ratio of surface area to body weight than adults, resulting in an elevated risk for dermal absorption.[3,45] Additionally, children have a decreased ability to detoxify substances. During growth, a child's developing systems are significantly more sensitive to damage. Children often spend more time outdoors where hazardous exposures are within closer proximity. From a behavioral standpoint, young children typically exhibit hand-to-mouth behavior and crawl on the ground, which predictably leads to the direct ingestion of potentially harmful substances. Children have an underdeveloped risk perception that can lead to harmful exposures from e-waste.[46] Finally, children have a longer life expectancy during which they would live with the handicaps that injuries or exposure to toxic substances can provoke.

Effects of Exposure

The short- and long-term effects of exposure to hazardous e-waste substances are not fully understood, however, there is research on the association between e-waste exposure and higher levels of chemicals and metals in human-derived biological samples.[3,47,48] The toxicity of many individual substances found in e-waste is well documented, however, the toxicity of the mixtures of substances likely to be encountered through e-waste recycling is less well known. Heavy metals and halogenated compounds appear to have a major influence on potential health risks.[3,24]

The potential adverse health effects of exposure to e-waste have been reviewed recently and may include changes in lung function, thyroid function, hormone expression, birth weight, birth outcomes, childhood growth rates, mental health, cognitive development, cytotoxicity, and genotoxicity.[3,28,43] It is also possible that exposure to hazardous chemicals produced by e-waste recycling may have carcinogenic effects and endocrine disrupting properties that could lead to lifelong changes due to neurodevelopment anomalies, abnormal reproductive development, intellectual impairment, and attention difficulties.[28,49] Elevated levels of 8-hydroxydeoxyguanosine, a urinary biomaker of generalized, cellular oxidative stress, were observed in the post-work-shift urine of e-waste workers.[47] One study of Chinese e-waste workers documented significantly higher levels of serum polybrominated diphenyl ethers (PBDEs) and thyroid-stimulating hormone (TSH) than found in the control group.[48] The increased exposure to PBDEs from e-waste recycling may lead to interference with the thyroid hormone system and other adverse health effects.[48] Decreased lung function has been observed in boys aged 8 to 9 years living in an e-waste recycling town but not in boys living in a control town.[43] Significant negative correlations between forced vital capacity, a measure of lung function, and blood chromium concentrations have been reported.[43] Lead is also an established neurotoxicant that can lead to intellectual impairment and damage to the nervous, blood, and reproductive systems. Research findings indicate there is no threshold below which lead exposure does not have adverse effects on a developing nervous system.[3,50] Brominated flame retardants have a long half-life and reportedly lead to impaired learning and memory function; altered thyroid, estrogen, and hormone systems; behavioral problems; and neurotoxicity. Cadmium tends to bioaccumulate and can be highly toxic, especially to kidneys and bones. Mercury is thought to cause damage to the brain and central nervous system, particularly during early development. The number of harmful substances that humans could be directly or indirectly exposed to by e-waste is vast and difficult to quantify. The concentrations of these materials are variable but often are notably high, especially within the actual e-waste sites. Even if the concentrations of these substances are low, the chemicals are often still toxic to humans and persistent in the environment. The heterogeneous nature of hazardous exposures contributes to the difficulties surrounding the study of the effects e-waste exposures.

There are additional aspects of e-waste exposure that may lead to adverse health outcomes. Even if daily exposure is low, cumulative exposure is often high and extremely hard to measure.[3,21] Even when the effects of a single chemical at certain levels are well studied the effects of the mixtures of hazardous e-waste substances are not well known. Within a mixture of chemicals, some substances may have synergistic or modifying effects that could be extremely harmful.[3,22] The reagents used in the recycling process, such cyanide and other strong leaching acids, may contribute to the hazardous chemical e-waste mixtures. Not only do the daily and cumulative doses of exposure matter when calculating risk, but also the timing, or “life stage of exposure” is highly significant.[51] Clearly, dismantling e-waste can also directly lead to injury. Certain individuals, such as children, are more vulnerable given the sensitivity of their developing systems. The timing of exposure also may indicate the expected duration of certain resulting health effects of exposure.

Much research is needed on e-waste exposure and potential adverse health effects. Strong evidence that links occupation exposure of hazardous e-waste substances to health effects is lacking. The potential causal relationship between exposure and observed negative effects requires additional, extensive research. Also, the combination of e-waste secondary chemicals and biological agents is unknown. For example, the interaction between lead and mercury with the malaria parasite requires further investigation.[52] On a very basic, human level, research and development of treatment measures for those exposed to hazardous e-waste materials is essential. Research on e-waste hazards can be limited by poor access to uncontrolled settings, limited resources, and political and ethical concerns. Monitoring and surveillance, especially of informal e-waste recycling operations, is sparse. Despite these research obstacles, further studies are vital. Not only are risk assessments of e-waste exposure critical, but also research that will help informal local, regional, and global e-waste recycling policy is urgently needed.

How the Health Care Sector Contributes to E-waste

By definition, health care waste encompasses all waste produced from health care facilities, research centers, and laboratories, as well as waste from medical activities. Approximately 80% of the waste generated by health care facilities is similar to general, domestic waste and is considered “nonhazardous.” The remaining 20% is considered “hazardous” as it may pose a chemical, radioactive, or physical hazard to the environment and to human health. Although the common form of health care waste includes syringes, needles, and expired pharmaceuticals, it is the discarded electrical health care equipment that comprises health care e-waste.[53] Health care facilities use, and thus discard, more specialized medical devices and equipment. Examples of such include, but are not limited to, sphygmomanometers, electrocardiograms, spectrophotometers, and microscopes.[54] Some of these devices and appliances come into direct contact with various chemicals and biologic agents that may be harmful to human health. Before disposal, medical equipment requires technical and safe treatment,[55] which includes disinfection before repair or recycling.[54] More research on the management practices of health care e-waste is essential.

There is a global effort, prompted by the Minamata convention,[56] to discontinue the use of mercury in health care by 2020. Mercury-containing thermometers and sphygmomanometers are being replaced with their respective electronic counterparts. This system-wide replacement of mercury-containing devices may, in the long run, increase the amount of health care e-waste. Health care facilities management needs to consider the life span of the medical devices they procure and then discard. E-waste management must be integrated into hospital management policies and plans. It is also essential that health care facilities establish waste registers for their EEE alongside the nonelectrical medical equipment inventories.[57] Health care facilities, organizations, providers, and professionals must not only follow proper e-waste management procedures but they must also encourage the use of regulated and safe e-waste recycling paths in an effort to ensure health at all levels.

E-waste Regulation and Policy

In the past, most e-waste regulations have been prompted by and focused on environmental protection. Recently, e-waste guidelines have been adopted and enforced because of human health concerns.[43] The 1989 Basel Convention, which has been ratified by 181 countries, prohibits the export of e-waste.[14] Despite export regulations this convention has a loophole that permits e-waste exportation if it is intended for "re-use." This detail leads to a large quantity of near end-of-life EEE being exported. These older electronic products have short life spans, if any at all, once they reach the export countries. As a result, the e-waste designated for "re-use" only ends up contributing to the e-waste problem in the developing, recipient countries.[42] Within the EU, the Waste Electrical and Electronic Equipment Directive requires manufacturers and importers within member states to take back their products from consumers and ensure sound environmental methods are used to dispose of the e-waste.[7,17]

One of the first steps toward e-waste regulation was made in 1988 when 4000 tons of toxic waste from Italy was dumped in Koko Port, Nigeria. This led to the promotion of the Harmful Waste Decree 4, which criminalized the transportation, deposit, import, selling, buying, or negotiating that involved trade of harmful waste in Nigeria. Failing to abide by this decree could lead to a life sentence in prison. Nigeria had a notable influence on the text of the Basel Convention and was also the first African country to sign and ratify the agreement.[58] Despite these actions, Nigeria currently faces considerable threats from e-waste. The Bamako Convention on the ban of the import into Africa and the control of transboundary movement and management of hazardous wastes within Africa is a treaty among African countries that prohibits the import of hazardous wastes into member countries.[17]

Several initiatives have attempted to raise awareness of the need for appropriate regulation to protect against the health consequences of improper e-waste recycling practices, including the following:

- the Libreville Declaration framed during the first Inter-Ministerial Conference on Health and Environment in Africa in 2008;
- the Busan Pledge for Action on Children's Environmental Health (2009);
- the Strategic Approach to Integrated Chemical Management's expanded Global Plan of Action, issued at the International Conference on Chemical Management (2012); and
- the Geneva Declaration on E-waste and Children's Health (2013).

A growing number of international organizations and initiatives have been formed to encourage adequate monitoring and regulation e-waste recycling, including the StEP Initiative; the Basel Action Network; the Silicon Valley Toxics Coalition; Toxics Link India; SCOPE Pakistan; and Greenpeace China. UNEP, United Nations University (UNU), PACE, the Federal Ministry for the Environment (Germany), the Nature Conservation and Nuclear Safety (Germany), and the National Institute of Environmental Health Sciences (US) are all involved with international research, advocacy, and regulation.[34] The World Health Organization's Children's Environmental Health team is working on e-waste and the effects on child health. This coordinated effort seeks to raise awareness, develop tools, and investigate solutions to children's exposures.[34]

There are several suggested methods to help guide the improvement and strengthening of e-waste policy. These methods entail Extended Producer Responsibility (EPR), Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Multi Criteria Analysis (MCA).[10] EPR promotes the "3 Rs": "Reduce, Reuse, and Recycle" and shifts the responsibility of safe e-waste recycling pathways from the municipal authorities to the producers.[59] As defined by The OECD this environmental policy approach provides a strong incentive for companies to produce easily recycled and less toxic electronics.[59] EPR is difficult to implement given the resistance of financially endowed producers. The LCA uses a "cradle-to-grave" approach to consider the environmental and total impact of a specific product. Obstacles arise from the lack of inventory data, particularly in developing countries, which is required to complete this assessment. The MFA traces a substance from production to application to recycling and disposal. As expected, it can be challenging to trace products. The MCA is a critical analysis tool for decision making as it provides a complete picture of alternative scenarios and solutions. Criteria are ranked according to shared priorities. With this technique, stakeholders can weigh the cost and benefits for all involved parties. Regulating recycling, particularly within the informal economic sector, is challenging. Banning informal recycling is typically ineffective because the practice is easily relocated due to the nonexistent requirements on labor or facilities. Incentive-based policies that protect human health and the environment must be proactive and practical.

CONCLUSION

E-waste recycling is necessary but it should be conducted in a safe and standardized manor. When possible, e-waste should be refurbished and reused as a complete product instead of dismantled.[15] When refurbishment in not possible, e-waste should be dismantled by trained, protected, and well-compensated workers in technologically advanced e-waste recycling facilities in both developed and developing countries.[42] There are several fundamental principles from which all e-waste regulation should be based on. First, acceptable risk thresholds for hazardous, secondary e-waste substances should not be different for developing and developed countries. However, the acceptable thresholds should be different for children and adults given the physical differences and pronounced vulnerabilities of children.[51] Completely eliminating the presence of toxic components in EEE, although efficient, is not realistic. Although there are research needs, educational and awareness programs on the potential risks of e-waste recycling also should be developed and implemented. These programs are of vital importance in developing countries.[51] Improving occupational conditions for all e-waste workers and striving for the eradication of child labor is non-negotiable. Interventions should be specific to the local culture, the geography, and the limitations of the particularly vulnerable communities. Policies that would provide incentives to promote safe, regulated, and recompensed recycling for e-waste should be universal.[42]

ACKNOWLEDGMENTS

The authors acknowledge Federico Magalini (UNU) and, Matthias Kern (UNEP), Evelyn Kortum (WHO), and Graham Alabaster (WHO) for their contributions.

References

1. Brune MN, Goldizen F, Neira M, et al. Health effects of exposure to e-waste. Lancet Glob Health 2013;1:e70.
2. United Nations Environment Program (UNEP), Division of Technology, Industry, and Economics, International Environmental Technology Center. E-waste volume I: inventory assessment manual. 2007. Available at: http://www.unep.org/ietc/Portals/136/Publications/Waste%20Management/EWasteManual_Vol1.pdf. Accessed October 14, 2014.
3. Duffert C, Brune MN, Prout K. Background document on exposures to e-waste. Geneva, Switzerland: World Health Organization.
4. United Nations (UN) Department of Economic and Social Affairs, Population Division. Word population prospects the 2012 Revision. 2013. Available at: http://esa.un.org/unpd/wpp/Documentation/pdf/WPP2012_Volume-I_Comprehensive-Tables.pdf. Accessed October 14, 2014.
5. StEP Initiative. StEP Annual Report. 2013. Available at: http://step-initiative.org/tl_files/step/StEP_AR/StEP_AR.html. Accessed October 14, 2014.
6. Lundgren K, International Labor Office (ILO). The global impact of e-waste: addressing the challenge. 2012. Available at: http://www.ilo.org/wcmsp5/groups/public/—ed_dialogue/—sector/documents/publication/wcms_196105.pdf. Accessed October 14, 2014.
7. Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Schnellmann M, Boni H. Global perspectives on e-waste. Environ Impact Assess Rev 2005;25:436—58.
8. United Nations University (UNU), Solve the E-waste Problem (StEP), Massachusetts Institute of Technology (MIT), National Center for Electronics Recycling (NCER). World e-waste map reveals national volumes, international flows. 2013. Available at: https://www.vie.unu.edu/file/get/11505.pdf. Accessed October 14, 2014.
9. Schluep M, Hagelüken C, Kuehr R, et al. Sustainable innovation & technology transfer industrial sector studies: recycling—from e-waste to resources. United Nations Environment Programme (UNEP) and StEP—solving the e-waste problem. 2009. Available at: http://www.unep.org/pdf/Recycling_From_e-waste_to_resources.pdf. Accessed October 14, 2014.
10. Gagliardi D, Mirabile M. Overview of OSH issues related to the e-waste management. Geneva, Switzerland: World Health Organization.
11. Puckett J, Byster L, Westervelt S, et al. Exporting harm: the high-tech trashing of Asia. Basel Action Network, Silicon Valley Toxics Coalition. Available at: http://www.ban.org/E-waste/technotrashfinalcomp.pdf. Accessed October 14, 2014.
12. Diaz-Barriga F. Evidence-based intervention programs to reduce children's exposure to chemicals in e-waste sites. Discussion paper for WHO Working Meeting on e-waste and children's health. 2013 [cited 2014 Sept 17];1—90.
13. Basel Convention, UNEP. The partnership for action on computing equipment (PACE). 2008. Available at: http://www.basel.int/Portals/4/Basel%20Convention/docs/pub/leaflets/leafPACE.pdf. Accessed October 14, 2014.
14. UNEP. Basel Convention on the control of transboundary movements of hazardous wastes and their disposal. 1992. Available at: http://www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf. Accessed October 14, 2014.
15. UNEP. Revised guideline on environmentally sound testing, refurbishment and repair of used computing equipment. Conference of the Parties to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. 2013. Available at: http://www.unep.org/chemicalsandwaste/Portals/9/Mercury/Waste%20management/3rd%20partnership%20meeting/session%203/[3-5]Basel%20Technical%20Guidelines.pdf. Accessed October 14, 2014.
16. Technical guidelines on transboundary movements of e-waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention. 2013. Available at: http://www.basel.int/Implementation/Ewaste/TechnicalGuidelines/tabid/2377/Default.aspx. Accessed October 14, 2014.
17. Ongondo FO,Williams ID, Cherrett TJ. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manag 2011;31:714—30.
18. Greenpeace. Where does e-waste end up? 2009. Available at: http://www.greenpeace.org/international/en/campaigns/toxics/electronics/the-e-waste-problem/where-does-e-waste-end-up/. Assessed October 14, 2014.
19. Cobbing M. Toxic tech: not in our backyard. Uncovering the hidden flows of e- waste. Report from Greenpeace International. 2008. Available at: http://www.greenpeace.org/international/Global/international/planet-2/report/2008/2/not-in-our-backyard.pdf. Assessed October 14, 2014.
20. Chi X, Streicher-Porte M, Wang MYL, Reuter MA. Informal electronic waste recycling: a sector review with special focus on China. Waste Manag 2011;31:731—41.
21. Chan JKY, Wong MH. A review of environmental fate, body burdens, and human health risk assessment of PCDD/Fs at two typical electronic waste recycling sites in China. Sci Tot Environ 2012;463-464:1111—23.
22. Chen A, Dietrich KN, Huo X, Ho S. Developmental neurotoxicants in e-waste: an emerging health concern. Environ Health Perspect 2010;119:431—8.
23. Frazzoli C, Orisakwe OE, Dragone R, Mantovani A. Diagnostic health risk assessment of electronic waste on the general population in developing countries scenarios. Environ Impact Assess Rev 2010;30:388—99.
24. Tsydenova O, Bengtsson M. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag 2011;31:45—58.
25. Wong CSC, Duzgoren-Aydin NS, Aydin A, Wong MH. Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. Environ Pollut 2007;148:62—72.
26. Wong CSC, Wu SC, Duzgoren-Aydin NS, Aydin A, Wong MH. Trace metal contamination of sediments in an e-waste processing village in China. Environ Pollut 2007;145:434—42.
27. Tue MN, Sudaryanto A, Minh TB, et al. Accumulation of polychlorinated biphenyls and brominated flame retardants in breast milk from women living in Vietnamese e-waste recycling sites. Sci Total Environ 2010;408:2155—62.

28. WHO. The Geneva declaration on e-waste and children's health. Available at: http://cerch.org/wp-content/uploads/Geneva-Declaration-final.pdf. Assessed October 14, 2014.
29. Seplveda A, Schluep M, Renaud FG, et al. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environ Impact Assess Rev 2010;30:28–41.
30. Horton LM, Mortensen ME, Iossifova Y, Marlena MW, Burgess P. What do we know of childhood exposures to metals (arsenic, cadmium, lead, and mercury) in emerging market countries? Int J Pediatr 2013;2013:1–13.
31. Breivik JM, Armitage FW, Jones KC. Tracking the global generation and exports of e-waste: do existing estimates add up? Environ Sci Technol 2014;48:8735–43.
32. Yu XZ, Gao Y, Wu SC, Zhang HB, Cheung KC, Wong MH. Distribution of polycyclic aromatic hydrocarbons in soils at Guiyu area of China, affected by recycling of electronic waste using primitive technologies. Chemosphere 2006;65:1500–9.
33. Fu J, Zhou Q, Liu J, et al. High levels of heavy metals in rice (Oryza *sativa* L.) from a typical e-waste recycling area in southeast China and its potential risk to human health. Chemosphere 2008;71:1269–75.
34. WHO. E-waste and child/vulnerable populations' health initiative concept note. 2013. Available at: http://www.step-initiative.org/tl_files/step/_downloads/UNU%20&%20WHO%20Survey%20on%20E-waste%20and%20its%20Health%20Impact%20on%20Children%20-%205%20August%202013.pdf. Accessed October 14, 2014.
35. WHO. Meeting report: WHO meeting on e-waste and child health. 2013. Available at: http://www.step-initiative.org/tl_files/step/_downloads/UNU%20&%20WHO%20Survey%20on%20E-waste%20and%20its%20Health%20Impact%20on%20Children%20-%205%20August%202013.pdf. Accessed October 14, 2014.
36. Seager D, Hieronymi K, McIntrye K, Guilcher H, van Rensburg RJ. Producer responsibility when WEEE has a value. Electronics goes green (EGG) 2014;1:9–12.
37. OECD. OECD Council Recommendation on the Environmentally Sound Management of Waste and OECD Technical Guidance for the Environmentally Sound Management of Specific Waste Streams: Used and Scrap Personal Computers. 2014. Available at: www.basel.int/industry/compartnership/docs/FinalApprovedReportESM-22March2010.pdf. Accessed October 14, 2014.
38. Xu X, Yang H, Chen A, et al. Birth outcomes related to informal e-waste recycling in Guiyu, China. Reprod Toxicol 2012;33:94–8.
39. Guo YY, Huo X, Wu KS, Liu JX, Zhang YL, Xu X. Carcinogenic polycyclic aromatic hydrocarbons in umbilical cord blood of human neonates from Guiyu, China. Sci Total Environ 2012;427:35–40.
40. Leung AOW, Cai ZW, Wong MH. Environmental contamination from electronic waste recycling at Guiyu, southeast China. J Mater Cycles Waste Manag 2006;8:2133.
41. Leung AOW, Luksemburg WJ, Wong AS, Wong MH. Spatial distribution of polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzofurans in soil and combusted residue at Guiyu, an electronic waste recycling site in southeast China. Environ Sci Technol 2007;41:2730–7.
42. The Lancet. Electronic waste – time to take stock. Lancet Glob 2013;381:2223.
43. Grant K, Goldizen FC, Sly PD, et al. Health consequences of exposure to e-waste: a systematic review. Lancet Glob Health 2013;1:e350–361.
44. Oteng-Ababio M. When necessity begets ongenuity: e-waste scavenging as a livelihood strategy in Accra, Ghana. Afr Stud Q 2012;13:1–21.
45. WHO. Environmental health criteria 237: principles for evaluating health risks in children associated with exposure to chemicals. Available at: http://www.who.int/ipcs/publications/ehc/ehc237.pdf. Accessed October 14, 2014.
46. Caravanos J, Clarke EE, Osei CS, Amoyaw-Osei Y. Exploratory health assessment of chemical exposures at e-waste recycling and scrapyard facility in Ghana. J Health Pollution 2013;4:11–22.
47. Wen S, Yang FX, Gong Y, et al. Elevated leves of urinary 8-hydroxy-2′-deoxyguanosine in male electrical and elctronic equipment dismantling workers exposed to high concentrations of polychlorinated dibenzo-*p*-dioxins and dibenzofurans, polybrominated diphenyl ethers, and polychlorinated biphenyls. Environ Sci & Technol 2008;42:4202–7.
48. Chen L, Chen D, Guo H, et al. Elevated serum polybrominated diphenyl ethers and thyroid-stimulation hormone associated with lymphocytic micronuclei in Chinese workers from an e-waste dismantling site. Environ Sci Technol 2008;42:2195–200.
49. WHO. State of the science of endocrine disrupting chemicals – 2012. Available at: http://www.who.int/ceh/publications/endocrine/en/. Accessed October 14, 2014.
50. Needleman H. Low level lead exposure: history and discovery. Ann Epidemiol 2009;19:235–8.
51. van den Berg, M. State of the art on risks of e-waste and children's health. Discussion paper for WHO Working Meeting on e-waste and children's health. 2013.
52. Silva IA, Nyland JF, Gorman A, et al. Mercury exposure, malaria, and serum antinuclear/antinucleolar antibodies in amazon populations in Brazil: a cross-sectional study. Environ Health 2004;3:11.
53. WHO. Safe management of wastes from health-care activities (2nd ed.). 2014. Available at: http://apps.who.int/iris/bitstream/10665/85349/1/9789241548564_eng.pdf?ua=1. Accessed October 14, 2014.
54. WHO. Medical equipment maintanance programme overview. 2011. Available at: http://whqlibdoc.who.int/publications/2011/9789241501538_eng.pdf. Accessed October 14, 2014.
55. Mannocci A, Zscheppang A, Torre G, et al. A pilot survey about waste management in European hospitals: focusing on electrical and electronic equipment. J Pub Health 2012;20:65–9.
56. UNEP. Minamata Convention on Mercury. Geneva, Switzerland: United Nations Environment Programme; 2013.
57. WHO. Needs Assessment for Medical Devices. 2011. Available at: http://whqlibdoc.who.int/publications/2011/9789241501385_eng.pdf. Accessed October 14, 2014.
58. Odubela MT, Soyombo O, Adegbite F, Ogungbuyi K. Transboundary illegal shipments of hazardous waste, toxic chemicals (pesticides) contraband chlorofluorohydrocarbons: the Nigerian experience. Fourth International Conference on Environmental Compliance and Enforcement 1996; Chiang Mai, Thailand.
59. Nnorom IC, Osibanjo O. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour Conser Recy 2008;52:843–58.