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Environmental and health impacts of informal electronic waste recycling

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Environmental and Health Impacts of Informal Electronic Waste Recycling

Chimere May Ohajinwa

Chimere May Ohajinwa (2018)

Environmental and Health Impacts of Informal Electronic Waste Recycling

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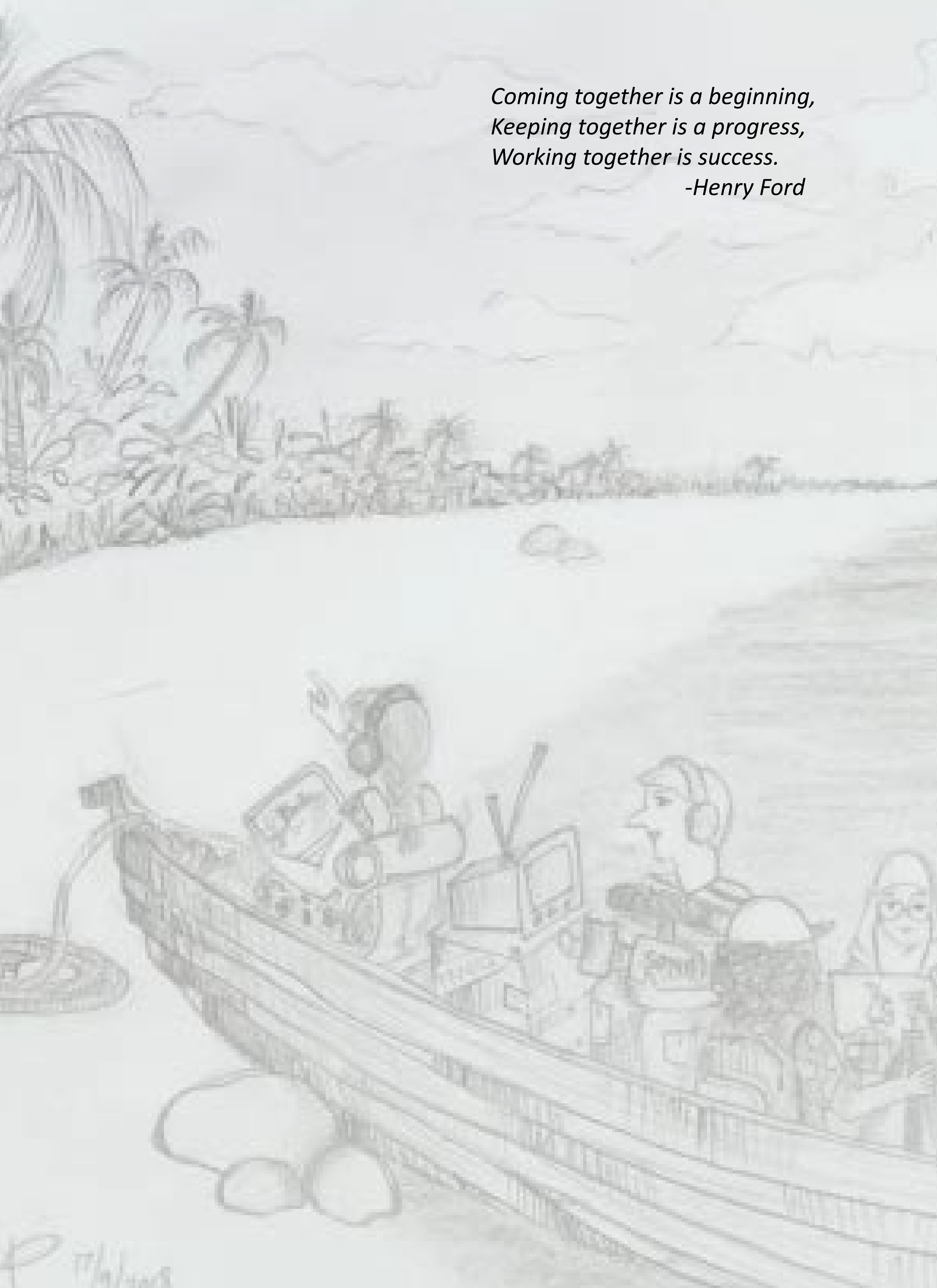

Coming together is a beginning,
Keeping together is a progress,
Working together is success.
-Henry Ford

Environmental and Health Impacts of Informal Electronic Waste Recycling

PROEFSCHRIFT

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This research was funded by NUFFIC (Netherlands Universities Foundation for International Cooperation).

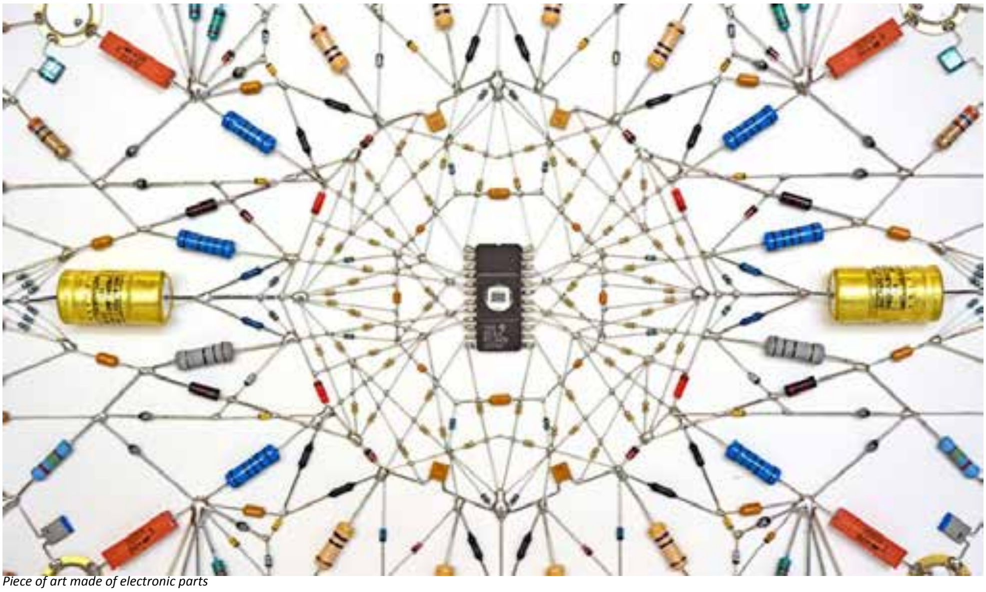
To my family on this PhD journey

Table of Contents

Chapter 1

General Introduction

Do you still remember your old electronic devices?



Piece of art made of electronic parts

Source: Technological mandala 02,
"Electronic echnology has become an important part in our daily life, almost something to worship"
- Leonardo Ulian

1.1 Background

Across the globe, electronic or electrical devices have become indispensable in our daily lives and the use of electronic electrical device is growing at great speed. It is characterized by an increasing number of users and rapid technological advances driven by efficiency, social and economic development. Many people now own multiple personal electronic devices such as information and communication technology (ICT) devices, but the life span of these devices is getting shorter mainly because they become obsolete more quickly compared to the past. In addition, most of these devices are disposed even before they become dysfunctional so as to make space for newer devices with better specifications/ functions. This is evident as most homes possess at least one obsolete electrical device lying somewhere, probably covered in dust and which has not been used in a long time. There is also increasing tendency to electric power previously non-electrical equipment (Baldé, *et al*., 2017; Baldé, *et al*., 2015; Lundgren, 2012. My interest in e-waste recycling sprang during my Master's project on medical waste handling which involved electronic medical equipment waste handling. My findings were quite overwhelming, hence the birth of this PhD research.

The exponentially growing demand for electronic equipment has led to a rapid increase in the rate of electronic waste (e-waste) generated (Baldé *et al*., 2015). E-waste, also known as Waste Electrical and Electronic Equipment (WEEE), consists of electrical and electronic devices at the end of their useful life which includes all separate components such as batteries, circuit boards, plastic casings, cathode-ray tubes, lead capacitors (Baldé, *et al*., 2015; Lundgren, 2012; Robinson, 2009). E-waste is one of the fastest growing municipal waste streams. The annual growth rate is 3–5%, which is approximately three times faster than other municipal solid waste. In 2016, 44.7 million metric tonnes (Mt) of e-waste were generated globally, with Asia generating the highest 18.2Mt (because of their population), Europe (12.3Mt), The Americas (11.3Mt), Africa (2.2Mt), and Oceania (0.7Mt); and this amount is expected to increase to 52.2 million metric tonnes by 2021 (Baldé *et al*., 2017). Only 20% (8.9Mt) of the e-waste generated is collected and recycled formally, the remaining (about 80%) is undocumented (Baldé *et al*., 2017), and is recycled in informal settings or are simply sent to dumpsites/landfills in many developing countries; but large quantities of informal recycling has been reported China, India, Philippines, Vietnam, Thailand, Ghana and Nigeria (Grant *et al*., 2013) Perkins *et al*., 2014). Informal electronic waste recycling includes the dismantling of end-of-life electronics to retrieve valuable elements using crude unsafe methods, without or with very little health and safety precaution. This recycling method releases hazardous substances to the environment (Wong *et al*., 2007a). While, formal electronic waste recycling facilities use specifically designed equipment to safely remove salvageable materials from obsolete electronics while protecting workers from adverse health effects. However, these centres are very expensive to build and run and are rare in less developed countries (Wang, 2008). Especially in countries with no national e-waste regulations, e-waste is treated informally along other general waste, causing health and environmental risks as the e-waste mixture chemicals are released into the environment.

In most developing countries, e-waste is managed informally usually through low-end management alternatives such as product reuse, refurbish/repairs, dismantling to recover valuable parts, disposal in landfills, and open burning. In developing countries there are lots of reuse and repair activities. However, e-waste recycling has provided employment and source of income for many. Also, there are significant economic values of materials recovered from e-waste, especially if the recovery activities are carried out in the developing countries where labour is cheap and environmental and health standards are lax or not enforced (Lundgren, 2012; Terada, 2012). The total value of raw materials present in e-waste is under estimated at 55 billion Euros in 2016, this value is expected to be higher if circular economy models are applied (Baldé *et al*., 2017).

The e-waste management challenges facing the developing countries include:- an absence of infrastructure for appropriate waste management, an absence of legislation dealing specifically with e-waste, an absence of any framework for end-of-life product take-back system, or implementation of extended producer responsibility (EPR) schemes. The take-back system is an ideal scenario aimed at reducing environmental impact. It is usually set up under national e-waste legislations where the e-waste is collected by designated organisations through retailers, municipal collection points and/or pick-up services. The e-waste is then transferred to a formal e-waste treatment facility where the materials are recovered and recycled. Extended Producer Responsibility (EPR) is a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various stages of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product (Lindhqvist, 2000). EPR focuses on the end-of-life/use treatment of products, and primarily aims at increasing the amount and degree of product recovery to reduce the environmental impact of waste materials. In most developing countries, people who are self-employed go from door-to-door to collect the e-waste, and sell to refurbishers and informal recyclers. These informal collections are not documented (Ogungbuyi *et al*., 2012; Baldé *et. al*, 2017). In Africa only 1% (4Kt) of e-waste is documented to be collected and recycled. And little information is available on the e-waste collection rate in Africa.

Informal work is defined as all economic activities by workers and economic units that are in law or in practice not or insufficiently covered by formal arrangements, i.e., beyond the reach of formal laws; Or Informal sector is any income-generating activities that operate outside the regulatory framework of the state (International Labour Office (ILO), 2014; Meagher, 2013). Workers are casually employed, often by family members, relatives or are self-employed and do not have job security or benefit from social protection (Okechukwu, 2014). In addition, many of them are not aware of available protections or their occupational legal rights. In developing countries, the informal sector is vast and cuts across several different economic fields, including e-waste recycling. It provides services at low cost and is characterised by unsafe working conditions and poor health standards (Fasanya & Onakoya, 2012,The Rockefeller foundation, 2014; Barnes *et al*., 2014). Informal economy flourishes in a context of soaring (formal) unemployment. As a fast growing sector, informal work provides employment for the majority of the African and Asian populations, covering 66% of employment in Sub-Saharan Africa and 82% in South Asia excluding employment in the agricultural sector. Most of the workers work mainly for economic benefits. In this sector, labour standards are not enforced, practices are unregulated or under-regulated, official governance is lacking, and the sector is generally overlooked (The Rockefeller foundation, 2014; Barnes *et al*., 2014). In Africa, over 300,000 work-related deaths, over 44,000 work-related injuries occurred, and over 49 million workers were absent from work for at least four days due to occupational accidents in 2008. Globally, an estimated 2.3 million work-related deaths occur annually, and the economic cost of work-related injury and illness is estimated at 4% of the world's GDP (Gross Domestic Product) (Takala *et al*., 2014; Hämäläinen, 2010). Furthermore, about 2.9 billion workers globally are estimated to be at risk at work, and about 3.5 years of healthy life are lost per 1000 workers globally. Figures of work-related injuries and deaths in the informal sector alone are unavailable. Employment in the informal sector is no longer a journey, but has become the destination of many, and it should be supported by the government (Sparks & Barnett, 2010).

Within the informal sector, the e-waste recycling industry is a young rapidly growing industry. It has created many employment opportunities; affordable access to electronics and parts used for repairs; a continuous supply of raw materials to manufacturers without further exploration of natural resources; and conservation of natural resources and energy required to manufacture new electronics from virgin resources. In Nigeria, the e-waste recycling sector has provided employment opportunities for about 80,000 people. Another advantage of e-waste recycling is that on the average a repair shop receives 20-50 electronic devices daily, and about 68% of the devices are successfully repaired. Unrepairable devices are used as parts for repairs, the remaining is stored for their perceived value for about 6 - 36 months before finally disposal with general waste or sold to scrap dealers, who dismantles to recover valuable materials (Ogungbuyi *et al*., 2012).

About 68% of the informal e-waste recycling involves labour-intensive manual dismantling, shredding, isolation of materials, open burning of plastics from electronics, heating of circuit boards, use of toxic acid baths for metal recovery as practiced in Asia, and open dump disposal (Manomaivibool, 2009, Wong *et al*., 2007b). These unsafe recycling techniques are used to recover valuable materials without or with very little technology to minimise exposure, thus allowing the emission of dangerous chemicals. Occupational safety and environmental protection are clearly not prioritised. In contrast, formal recycling is carried out by organisations with focus on toxicity and pollution control and has an environment, health and safety system in place. Formal recycling also operates under relevant legislations and policies. It involves big-scale investment in infrastructure, high operation cost and overhead internalized environmental cost subsidized by the government.

1.1.1 Legislative Responses to E-waste Management

Due to the international attention on the challenges of informal e-waste recycling, there has been a number of international regulations such as the 1989 Basel convention (Basel convention and UNEP, 1989), the 1991 Bamako Convention (UNEP, 1991), the 1998 Rotterdam convention (UNEP, 2004), 2001 Stockholm convention, 2001 Aarhus Convention (UNECE, 2002), the 2003 Waste Electrical and Electronic Equipment (WEEE) directive (EU, 2003), and the 2006 Nairobi Declaration on Environmentally sound management of e-waste (UNEP, 2006), among others. Countries are encouraged to domesticate these regulations. There is an increase of 44% on the number of countries adopting e-waste regulations since 2014. By 2017, there are 67 countries that have e-waste management laws, of which Nigeria is one of the few countries in Africa that have enacted specific national e-waste policies and legislations. However, the existence of e-waste policies and legislations does not imply effective enforcement of the laws, or a presence of infrastructure for e-waste management. Many of the countries, also do not have the correct statistics of amount of e-waste imported or generated (Baldé *et al*., 2017).

In 2007, Nigeria established a body- National Environmental Standards and Regulations Enforcement Agency (NESREA). NESREA is in charge of e-waste management and environmental protection. Nigeria is a signatory to international treaties and has e-waste specific national legislations regulating import and management of e-waste in Nigeria. Nigerian legislations covering e-waste management include, The National Environmental (Electrical/Electronic Sector) Regulations, (2011), The National Environmental Regulations and the Harmful Waste Act (2011), The National Toxic Dump Watch Programme (NTCWP) (2011), and the guide for Importers of UEEE (Amachree, 2013); among others. Unfortunately, the enforcement of these legislations are weak in developing countries (Terada, 2012). Despite the increasing volumes of e-waste generated over the years, collection and recycling of e-waste are still not improved in developing countries (Ackah, 2017; Baldé *et al*., 2017). Nigeria imports the largest volume of new and used electronic and electrical equipment in Africa (Ogungbuyi *et al*., 2012). In 2005, an estimated 60,000 metric tonnes of used or scrap computers were imported and about 25–75% of these were non-functional (Osibanjo & Nnorom, 2007), (Puckett, *et al*., 2005). Following the stricter legislations, in 2016 only about 19% of the imports were non-functional (Baldé *et al*., 2017). The amount of e-waste generated in Nigeria increased from 219 kilo tonnes in 2014. (Baldé *et al*., 2015), to 277 kilo tonnes in 2016 (Baldé *et al*., 2017). This is an increase of 26% in just 2 years. The majority of the e-waste is recycled in an unsafe/informal manner (Ogungbuyi *et al*., 2012; Baldé *et al*., 2017), releasing chemicals into the surrounding environment, which consequently has become a serious burden on the Nigerian environment and health. Functional but used (second-hand) electronical devices are not considered as hazardous.

1.1.2 Justification for the Study

E-waste contains over 1000 different substances, some of which are hazardous (such as lead, mercury, cadmium, arsenic and beryllium) and persistent organic pollutants (POPs) (including polychlorinated biphenyls and brominated flame retardants) (UNEP-DTIE, 2007). These substances are released as mixture chemicals, so is difficult to assess the effects of exposure to a specific element or compound. When e-waste is improperly recycled or disposed at the landfills or dumpsites, heavy metals, persistent organic pollutants and other chemicals from e-waste are released into the environment compromising the quality of air, water and soil, and affect the biodiversity (animals and plants) in the immediate environment. These hazardous substances can travel hundreds of miles away from the recycling sites, thereby increasing the risk of exposure to a wider range of people and other living organisms. Some pollutants may remain in the soil for a long time, changing the soil chemistry, and may contaminate surface and underground water. The pollutants may also be harmful to micro-organisms in the soil as well as animals that relay on the micro-organisms.

Metal pollution can also affect the plants causing phytotoxicity resulting in weak plant growth, reduced nutrient uptake, reduce nitrogen fixation in legume plants, disorders in plants metabolism (Guala *et al*.; 2010). Metals released into the environment can also settle into the sediment, which would be eventually taken up by aquatic macrophytes and other aquatic organisms (Peng *et al*., 2007). Ingestion of mercury by fish can cause gill damage, and bio-accumulation in organisms like fish can also lead to contamination of the food chain, for example ingestion of mercury contaminated fish can cause neurological problems in humans. In some Asian countries, acids are used to extract precious metals from e-waste. Acidification of the surface water can disrupt marine biodiversity, leading to the reduction of some species. In addition, heavy metals and POPs are non-biodegradable, highly persistent in the environment, and can disturb the ecological balance of the aquatic environment, thus affecting the diversity of the aquatic organisms depending on the extent of the pollution (Ayandiran *et al*., 2009).

The primary and secondary exposure to these mixtures of chemicals is generally via inhalation, dermal contact and ingestion of contaminated soil, dust, air, water, and food. Animals and humans can be exposed via multiple routes. The health effects from exposure to e-waste mixture chemical are a complex process which depend on the route, duration, and frequency of exposure, and age at exposure. Studies have shown that exposure to the mixture of chemicals emitted during e-waste processing induces adverse effects including eye irritation, asthma, acute bronchitis, severe headaches, abdominal pain skin disease, under-development of the brain in children (Wang *et al*., 2012), damage to the nervous system, malfunctioning of the kidneys, respiratory problems, endocrine disruption, adverse pregnancy and birth outcomes, and poor health burden perpetuated through the mother-to-child etc. (Lundgren, 2012; Frazzoli *et al*., 2010; Grant *et al*., 2013). Children are a particularly sensitive group because of additional routes of exposure (e g, breastfeeding and placental exposures), high-risk behaviours (e g, hand-to-mouth activities in early years) (WHO), 2005) Exposure to children can result in not only immediate health effects but health effects at later life. These health problems are most evident when there is direct occupational exposure like in the case of informal e-waste recycling in family homes. Children of e-waste recycling workers also face take-home contamination from their parents' clothes and skin and direct high-level exposure if recycling is taking place in their homes (Grant *et al*., 2013) Despite, the draw backs associated with informal e-waste recycling, it creates employment and livelihood opportunities for many families and their dependents, especially in countries with high unemployment rate. Therefore any policy should consider the socio-economic benefit of this sector, which helps people to earn a decent living without choosing between poverty and poison. This situation in Nigeria is a typical case of informal e-waste recycling practices in countries that lack the resources for safe e-waste recycling. There is low public awareness of the health and the environment risks inherent in unsafe recycling of e-waste in Nigeria. This poses a challenge to policy makers to design effective environmentally sound e-waste management strategies, or tailor made intervention programmes for the reduction/prevention of the negative health effects of informal e-waste recycling. Currently, enforcement of e-waste regulations in Nigeria is weak. The regulations appear to be only made through the lens of the formal sector, which does not consider the challenges and benefits of the informal sector. Therefore, the suggestion that there could more appropriate tailor made intervention programmes in tackling the negative effects of e-waste recycling may be an effective strategy to explore. That strategy must aim to improve the working conditions in informal settings and consider the inputs from the informal sector in decision making processes. This PhD research stems from these concerns. Below is the conceptual framework of impact of informal e-waste recycling, as well as this study. The data and recommendations for better e-waste management offered in this research can be applied in similar situation like Nigeria.

1.1.3 Objectives

Considering the health risks of exposure to e-waste mixture chemicals, the focus of this PhD research is on the impact of informal e-waste recycling on the health of e-waste workers and the environment, this study therefore aims to answer the following questions:

- Are e-waste workers in Nigeria aware of health risks inherent in their daily jobs and what factor influences their awareness?

- What is the prevalence and injury pattern among e-waste workers in the informal sector in Nigeria?

- What is the environmental impact of informal electronic waste recycling on metal, concentrations in soils and dusts?

- Polybrominated Diphenyl Ethers (PBDEs) being one of the most harmful substance, what quantity of Polybrominated Diphenyl Ethers (PBDEs) are released into soils and dusts as a result of various activities at informal electronic waste recycling sites?

- Are there health risks associated with exposure to metal and PBDE at informal e-waste recycling sites? What are the estimated health risks?

Conceptual Framework of Impact of Informal E-waste Recycling

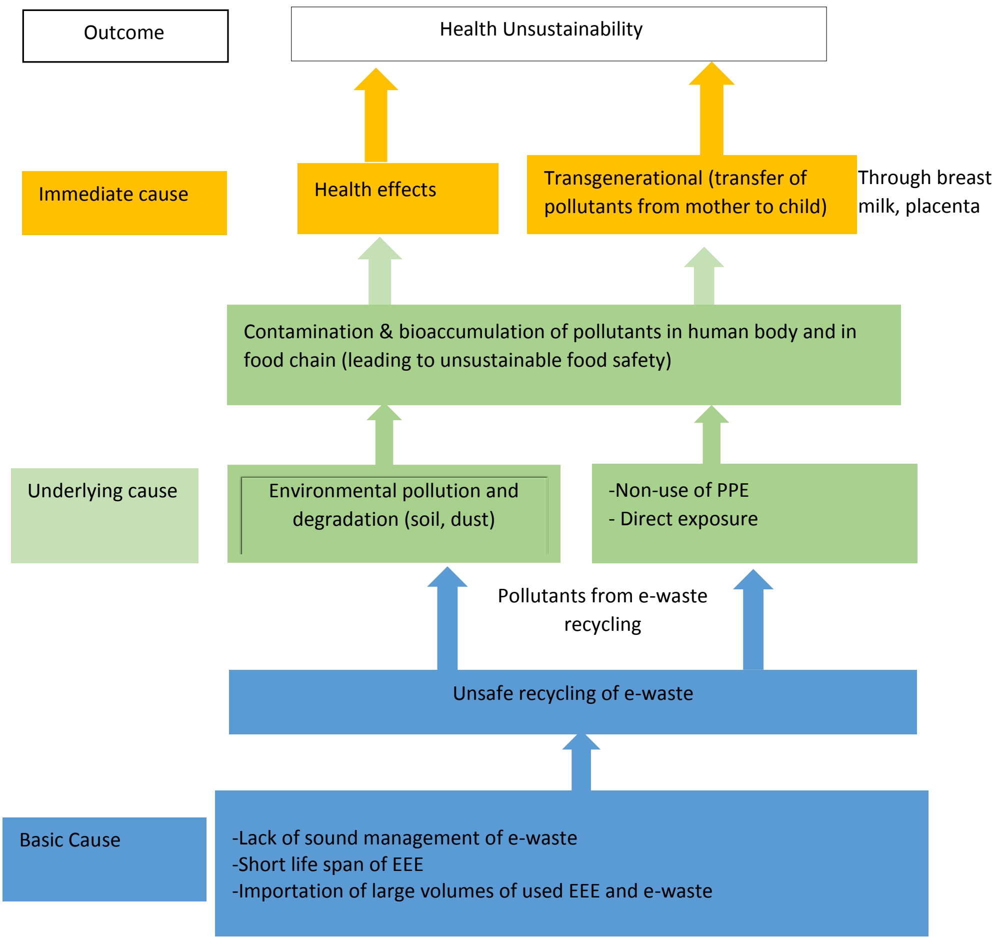


Figure 1.1 Conceptual Framework of Impact of Informal E-waste Recycling

1.2 Methods

1.2.1 Study Location

Figure 1.2: Map of Nigeria showing the Study Locations

The study took place in Nigeria. Nigeria is Africa's most populous nation. Nigeria is grouped into six geopolitical zones and has 36 states and the federal capital territory-Abuja. Nigeria runs three tiers of government structure; Federal Government, State Government and Local Government. The population is estimated at more than 178 million people from the last 2006 census. The population is characterized by a strong rural to urban migration, and annual growth rate estimates are over 3%. As a federation, environmental regulation in the country concerns the thirty six states and one federal capital territory. Each one is mainly responsible for its own environmental issues under various environmental and planning laws. The apex body in Nigeria is the Federal Ministry of Environment with the National Environmental Standards and Regulations Enforcement Agency as the main enforcement body.

The study took place in three cities (Lagos, Ibadan, and Aba) where e-waste is recycled/activities take place. These are some of Nigeria's busiest cities and commercial centers, which attract lots of migrants in search of greener pasture. These cities are densely populated and import a wide range of electronic products. Ibadan (in Oyo State) and Lagos are located in the South-Western and Aba (in Abia State) is located in the South-Eastern geopolitical zones of the country, respectively. The emphasis of the study will be on national tracer products based on prevalence in the market. These national tracer products are the information and communication technologies (ICT) products such as televisions, computers, and mobile phones.

Lagos is Africa's largest city, one of the world's largest cities and the economic centre of Nigeria with a population of 21 million. Lagos has developed into West Africa's main entry point for used and end-of-life electrical and electronic equipment. Annually 71,000 tonnes of used electronics enter Nigeria through the two main sea ports in Lagos (Baldé *et al*., 2017). This quantity excludes importation by air, and personal luggage. Although this equipment is mostly refurbished and sold to households and traders from Nigeria and other West and Central African countries, this sector generates significant amounts of e-waste, a problem that was first brought to public attention in 2005 with the film "The digital dump" by the NGO Basel Action Network (BAN). Lagos has very diverse ethnic groups with Yorubas as the dominant ethnic group. Ibadan is also a major urban settlement and commercial centre in the southwest of Nigeria. Yorubas are the major ethnic group in Ibadan. Aba is a major urban settlement and commercial centre in the southeast of Nigeria. The major ethnic group in Aba is the Igbos. Aba has high lots of markets, industries and fabricating industries. It is surrounded by small villages, towns and other states which depend on Aba for refurbished electronics. The major ethnic group in Aba is the Igbos.

1.2.2 Study Design

This study will adopt comparative cross-sectional study design. A comparative cross-sectional study is a study carried out at one time point or over a short period comparing multiple groups. Cross sectional studies provide a 'snapshot' of the outcome and the characteristics associated with the outcome, at a specific point in time. Cross-sectional studies indicate associations that may exist and are therefore useful in generating hypotheses for future research. Therefore, the comparative cross-sectional study was adopted over other study designs because it would help find the prevalence of health and environmental problems associated with e-waste recycling in Nigeria at a given time point. A multi-stage random systematic sampling technique was used to select the participants from each study location.

Stage one: Selection of a minimum of two study sites from the list of sites per study location

Stage two: Stratification of e-waste workers by type of e-waste recycled

Stage three: Selection of units/clusters

Stage four: Systematic selection of eligible participants from the units

1.2.3 Study Sites

At each study location (city), there were a couple of areas where e-waste is recycled, of which two major e-waste recycling areas were selected. In Lagos, the selected areas were the Computer village Ikeja and the Alaba international market Ojor. Alaba international market is the largest market for new and second-hand electronics in West Africa, with approximately ten to fifteen containers arriving daily from Europe and Asia (with each container containing about 400,000 second-hand units) (Osibanjo & Nnorom, 2007). Computer village Ikeja is a popular place where electronics and their parts (new and second hand) can be purchased and repaired in Lagos. In Ibadan, the selected sites were Ogunpa and Queens Cinema areas. Ogunpa area is known for its activities in scrap/second-hand businesses, which include electronics, while Queens cinema is known for sales and repair of both new and second-hand electronics. In Aba, the shopping centre and Port-Harcourt Road/Cementary and Jubilee road/St Michael’s Road were selected. The shopping center area is the biggest market for new and used electronics, while the Port-Harcourt road/Cemetery area is known as an area for scrap/second-hand metal businesses in Aba.

In each selected study area, two sampling e-waste recycling sites and a control site were selected randomly in order to ensure sufficient samples for the required sample size. Within the sampling sites, there is a mix of recycling units (repair workshops, dismantling units, non-electronics shops, offices, and so on) where various e-waste and non e-waste products are processed/sold. The open burning sites are usually far from the other sampling units. Burning sites were also selected at each location. Each sampling site was comprised of hundreds of units/clusters/shops where e-waste is either repaired/refurbished or dismantled/recycled. At each sampling site, systematic sampling techniques were used to select the recycling units. The participants (e-waste workers) were selected from the recycling units to ensure that the selected participants are a representative sample of the selected area. Control groups were also selected from the area. Information on the participant were used to answer research question 1 and 6.

Various E-waste Recycling Sites
Photo credit: Chimere May Ohajinwa, 2015

1.2.4 Study Population

The e-waste workers were split into two job designations (repairers and dismantlers/scavengers). Repairers repair or refurbish old and/or non-functioning electric and electronic equipment into second-hand and functioning equipment either by replacing or repairing defective components and/or by performing cleaning and repair activities in order to make the second hand equipment appealing to the customers. They extend the life time of equipment and feed the second hand market. Most refurbishers also engage in marketing and sales of the refurbished products. Most refurbishers typically specialize on a distinct group of products such as cooling and freezing equipment, air-conditioners, small household equipment, TVs, computers or mobile phones. Dismantlers collect/scavenge, dismantle, and burn e-waste to recover valuable materials. The majority of the scavengers/collectors also engage in dismantling of collected e-waste while some focus on only collection. Informal collectors are typically connected to the scrap metal business, therefore collectors usually do not solely focus on e-waste, but usually on several similar types of waste at the same time.

Butchers were selected as participants for the control group in each study location, because like e-waste workers, butchers constitute a male dominated profession of a comparable socio-economic status. Although a small part of the meat sector is regulated the government, it is also largely an informal sector. Moreover, butchers are also engaged in small-scale enterprises. They make a living from slaughtering and selling meat in abattoirs and markets within the city. Their work involves contact with live animals, their carcasses, blood and body fluids. The inclusion criteria for selecting the study population include those who have been working on e-waste/ used electronics/butchering for at least six months. The person must be at least 18years, and must consent to participate in the study.

1.2.5 Sample Size Determination for the Participants

When conducting research, it is usually impractical to study the whole target population, therefore a subset of the target population which adequately represents the target population is sampled(selected), and every individual has equal chance of been selected. If the sample is small, the results cannot be generalized to the population as the sample is not representative of the target population, and may not be able to detect the difference between groups. On the other hand, if the sample is too large, resources are wasted. Therefore, calculation of an adequate sample size required to be able to arrive at ethically and scientifically valid results. For this study we employed the sample size formula for a comparative study by Kirkwood 2003. In the literature used for the sample size calculation, the solid waste workers had higher health effects (systolic blood pressure) than the workers from control sites (Adienbo *et al*., 2013) Information on the environmental samples were used to answer research question 3,4 and 5.

Using formula for comparative study by (Kirkwood, 2003)

$$n = \frac{2(Z_{\alpha/2}+Z_{1-\beta})^2\ \sigma^2}{(\mu_1 - \mu_2)^2}$$

Where, n = required sample size

$Z_{\alpha/2}$ = Standard normal deviation corresponding to 95% confidence level set at 1.96

$Z_{1-\beta}$ = Standard normal deviation corresponding to 80% statistical power set at 0.84

σ^2 = Standard deviation of the outcome, set at 19.48 (Adienbo *et.al* 2013)

μ_1 = Mean Outcome of experimental group, set at 134.04 (Adienbo *et.al* 2013)

μ_2 = Mean outcome of control group, set at 124.95 (Adienbo *et.al* 2013)

$$n = \frac{2(1.96 + 0.84)^2\ (19.48)^2}{(134.04 - 124.95)^2}$$

$$n = \frac{2(7.28)\ (379.4704)}{(9.09)^2} = 66.8$$

$n = 67$

Calculating for 10% non-response rate

$$n_f = \frac{n}{1 - NR}$$

Where NR= 10% non-response rate

n_f = Adjusted sample size due to attrition

$$n_f = \frac{67}{1 - 10\%}$$

$n_f = 74$

Therefore, the sample size was set at 74 cases and 74 controls =148 for each study location; for three study locations, 444 participants were sampled.

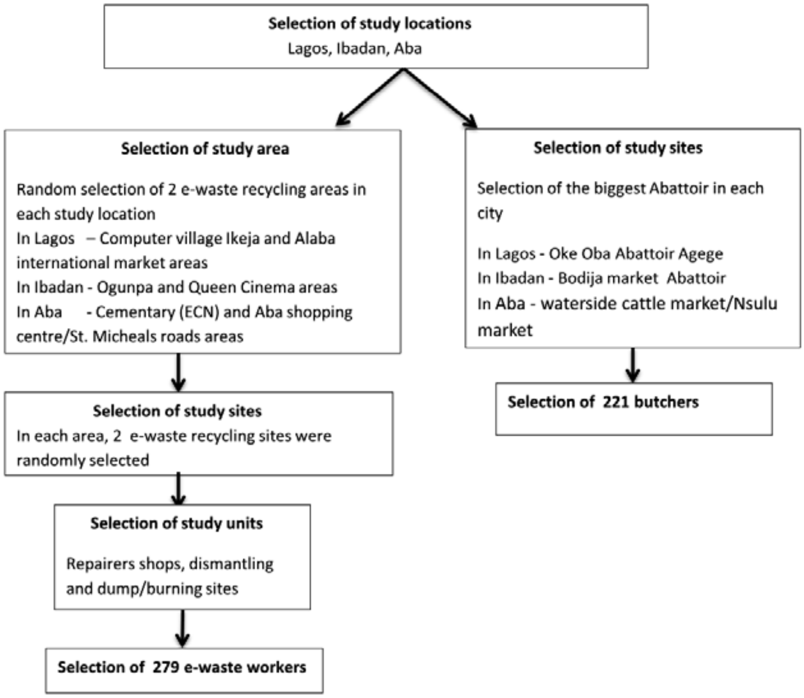


Figure 1.3: Schematic Diagram of Selection of Study Participants

1.2.6 Data Collection from Participants

A semi-structured interviewer-administered questionnaire containing open- and closed-ended questions (see appendix 1) was used to obtain information from the respondents between May and October 2015. One week prior to the actual data collection period, the questionnaire was pre-tested at an area different from the selected sampling areas and the questions were modified based on the experiences gained during the pre-test. Daily monitoring and evaluation was carried out to ensure accurate data collection. The workers were interviewed on their socio-demographic backgrounds, income, occupational history, knowledge, attitude, and work practices (KAP) to assess their awareness level. Information on the health problems experienced, injuries, lung function using peak flow meter, Body Mass Index (BMI) using studio-meter, and cardiovascular parameters using sphygmomanometer. In-depth interview guide and observation checklist was used to obtain information from participants and stakeholders. The questionnaires were serially numbered, to remove identifiers, for retrieval and to ensure completeness. The numbering on the questionnaires was also used to correlate information on questionnaire with other parameters obtained from participants. The data collection instruments will be pre-tested, modified based on information collected, and pre-tested again on 20 participants, and results compared to ensure reliability.

1.2.7 Ethical Considerations

Ethical approval was obtained from the University of Ibadan/University College Hospital Ethical Review Board (No. UI/EC/15/0096), see attached in the appendix. Verbal and written consent of the workers was obtained at the start of the interview, after explaining to the workers their full rights to refuse and to withdraw at any time during the interview. To ensure that the participant remains anonymous each questionnaire was coded with number identifiers. They were also assured that the data will not be used for other purposes than for scientific reasons and for the development of safety promotion programs for the sector. Permission to conduct the study was also obtained from the butchers' union at each abattoir/market and from association of second-hand electronics dealers at each study site.

1.2.8 Environmental (Soil and Dust) Sampling

Environmental samples (soil and dust) were sampled to also investigate the impact of informal e-waste recycling. To know the adequate sample size required to be able to arrive at scientifically valid results, we used the formula below for comparing e-waste sites and the control sites. In the literature used for the sample size calculation, the samples from the e-waste workshop had higher $\sum_8$PBDE concentrations than the samples from the control sites (Leung *et al*., 2008)

1.2.9 Sample size determination for soil and dust sampling

Using the formula for comparative studies by (Kirkwood, 2003):

$$n = \frac{2(Z_{\alpha/2}+Z_{1-\beta})^2\,\sigma^2}{(\mu_1 - \mu_2)^2}$$

Where,

n = required sample size

$Z_{\alpha/2}$ = Standard normal deviation corresponding to 95% confidence level set at 1.96

$Z_{1-\beta}$ = Standard normal deviation corresponding to 80% statistical power set at 0.84

σ^2 = Standard deviation of the outcome, set at 4200ng/g (Leung *et al*., 2008)

μ_1 = Mean Outcome of the experimental group, set at 13600ng/g (Leung *et al*., 2008)

μ_2 = Mean outcome of the control group, set at 144ng/g (Leung *et al*., 2008)

$$n = \frac{2(1.96 + 0.84)^2\,(4{,}200)^2}{(13{,}600 - 144)^2}$$

$$n = \frac{2(7.84)\,(4{,}200)^2}{(13{,}456)^2} = 1.5,\ \text{approx. } n = 2$$

Thus, a minimum of two soil samples from the control sites and for each category of e-waste with focus on the four tracer products (TV, mobile phone, computer, and fridge/Air conditioner) was sampled from the e-waste recycling sites in each study location. At each e-waste recycling site, three soil samples of different depths (0-10cm, 10-20cm, 20-30cm) were collected, and where was not possible to collect soil samples, available dust samples (floor dust and/or roadside) were collected, mostly from the repair sites/workshops. Direct dust samples were also collected from inside an outside the body of electronic devices. Three types of e-waste recycling activities sites (burning sites, dismantling sites, and repair sites/shops) were sampled and analysed. In Alaba, Lagos, we found only one big e-waste burning site, which is the largest, oldest, and most studied e-waste burning and dismantling site in Nigeria. In Ogunpa, Ibadan and Cemetery area Aba, the burning sites/spots were much smaller but more spread out in small clusters around the areas.

The control sites were between 100 and 500 meters away from the e-waste recycling sites, and consisted of areas with reduced human activity such as play grounds, parks, fields, and a university garden. Historical information on the control site were taken to ensure that that the control sites has not been used as e-waste recycling site in the past. The purpose of the control site was to serve as a base line against which the results of the soil sampling study could be evaluated. The locations of the sampling spots were georeferenced using a global positioning system (GPS) application on a phone.

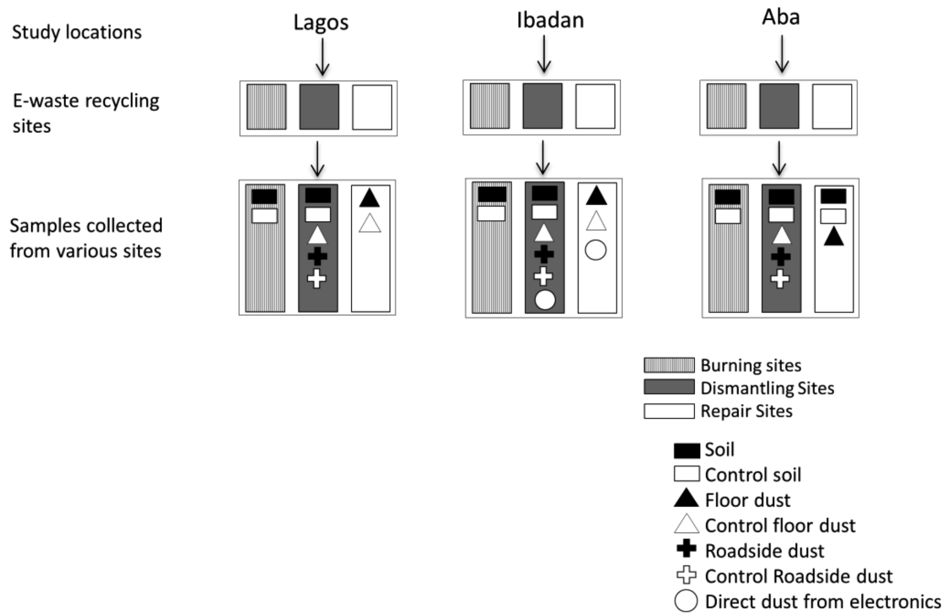


Figure 1.4: Schematic Diagram of Sample Collection for Metal Analysis

The samples were collected between May and November 2015. For soil sampling, each site was divided into grids of about 10m radius, and samples were systematically collected from 3 to 6 points within the site. The samples were bulked together for the top soil (0-10 cm depth) to form a composite representative sample for the specific site. The soil samples were collected using a soil auger, and a soil trowel was used in the transfer of soil from the auger into sample wraps. To avoid cross contamination, the soil probe/auger and trowel were decontaminated (cleaned first with a brush and wiped thoroughly with wet wipes) before each sample collection at each sampling site. Dust samples were collected using plastic brushes to gently sweep the dust and collect it with a dustpan. On the field, the soil and dust samples were wrapped in a treated aluminum foil (treated with acetone and oven dried at 120°C to ensure no traces of POPs in the aluminum foil), labelled, and transported to the laboratory. Soil and dust samples were later air dried for 7 days, avoiding exposure to sunlight homogenized (ground with a mortar and pestle), and sieved through a 1 mm mesh sieve to remove bigger particles, transferred into treated aluminum foil (for metal analysis) and then into a zip-lock bag, and stored at -20 C. Samples for PBDE analysis were transferred into treated individual 10ml amber bottles, labelled and stored at -20º C until shipping to the laboratory for analysis. The amber bottles were washed with tap water and laboratory detergent, rinsed with copious amounts of tap water, rinsed with distilled water for 3 times, then rinsed acetone, hexane, and oven dried. Detail of the laboratory analyis of the samples are in the chapters 3 and 4.

Figure 1.5: Soil Sampling using Dutch Soil Auger (left) at one of the E-waste Recycling Sites
Photo credit: Chimere May Ohajinwa, 2015

1.3 Thesis Outline

The study described the level of awareness of the dangers and impacts of informal e-waste recycling. The thesis comprises seven chapters. The present chapter gives a general overview of the topic and presents the research aims, methods and steps used in the study. Chapter 2 presents the Health Risks Awareness level of the informal e-waste workers on the dangers associated with their daily jobs. The awareness level was determined by assessing the knowledge, attitude, and work practices of the e-waste workers compared to their counterparts in the same informal sector. Chapter 3 unveils impact of informal Electronic Waste Recycling activities on Metal Concentrations in Soils and Dusts. Chapter 4 also unveils Polybrominated Diphenyl Ethers (PBDEs) Concentrations in Soils and Dusts as a result of various activities at Informal Electronic Waste Recycling sites. The environmental impact of the recycling was determined by detailed analysis of effects of various e-waste recycling activities in different types of samples – soil, floor dust, roadside dust, and direct dust from the electronics. Based on the findings, the health effects were assessed. Chapter 5 presents the current prevalence and injury patterns of e-waste workers. Chapter 6 estimates the health risks exposure to e-waste mixture chemicals (PBDE) on the e-waste workers, the synthesis of the findings, and discusses strategies appropriate effective e-waste management in informal sector.

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Chapter 2

Health Risks Awareness of Electronic Waste Workers in the Informal Sector in Nigeria

Based on article:

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"The mind once stretched by a new idea, never returns to its original dimensions"

– Ralph Waldo Emerson

Data Collection using Interviewer-Administered Questionnaire
Photo credit: Chimere May Ohajinwa, 2015

Abstract: Insight into the health risk awareness levels of e-waste workers is important as it may offer opportunities for better e-waste recycling management strategies to reduce the health effects of informal e-waste recycling. Therefore, this study assessed the knowledge, attitude, and practices associated with occupational health risk awareness of e-waste workers compared with a control group (butchers) in the informal sector in Nigeria. A cross-sectional study was used to assess health risk awareness of 279 e-waste workers (repairers and dismantlers) and 221 butchers from the informal sector in three locations in Nigeria in 2015. A questionnaire was used to obtain information on socio-demographic backgrounds, occupational history, knowledge, attitude, and work practices. The data was analysed using Analysis of Variance. The three job designations had significantly different knowledge, attitude, and practice mean scores (p = 0.000), with butchers consistently having the highest mean scores. Only 43% of e-waste workers could mention one or more Personal Protective Equipment needed for their job compared with 70% of the butchers. The health risk awareness level of the e-waste workers was significantly lower compared with their counterparts in the same informal sector. A positive correlation existed between the workers' knowledge and their attitude and practice. Therefore, increasing the workers' knowledge may decrease risky practices.

Keywords: electronic waste workers; health risk knowledge; attitude; practice; informal sector; informal economy; Nigeria

2.1. Introduction

Across the world, electronic or electrical devices have become indispensable in our daily lives, which have led to an exponential demand for electronic equipment and a rapid increase in the rate of electronic waste (e-waste) generation [1]. E-waste, also known as Waste Electrical and Electronic Equipment (WEEE), consists of electrical and electronic devices including all separate components such as batteries at the end of their useful life [1–4]. E-waste is one of the fastest growing municipal waste streams. The annual growth rate is 3–5%, which is approximately three times faster than other municipal solid waste. Globally, 50 million metric tons of e-waste is estimated to be generated in 2018 [1]. E-waste contains over 1000 different substances, some of which are hazardous substances (such as lead, mercury, cadmium, arsenic and beryllium) and persistent organic pollutants (including polychlorinated biphenyls and brominated flame retardants) [5]. About 80% of the e-waste generated globally is recycled in informal settings in developing countries such as Nigeria, Ghana, China and India [6].

Informal work is defined as all economic activities by workers and economic units that are in law or in practice not or insufficiently covered by formal arrangements, i.e., beyond the reach of formal laws [7]. Workers are casually employed, often by family members or are self-employed and do not have job security or benefit from social protection [8]. In addition many of them are not aware of available protections or their legal rights. In developing countries, the informal sector is vast and cuts across several different economic fields, including e-waste recycling. It provides services at low cost and is characterised by unsafe working conditions and poor health standards [9–11]. Informal economy flourishes in a context of soaring unemployment (formal). As a fast growing sector, informal work provides employment for the majority of the African and Asian populations, covering 66% of employment in Sub-Saharan Africa and 82% in South Asia excluding employment in the agricultural sector [10]. Most of the workers work mainly for economic benefits. In this sector, labour standards are not enforced, lack of regulations prevails, official governance is lacking, and the sector is generally overlooked [10,11]. In Africa, over 300,000 work-related deaths, over 44,000 work-related injuries occurred, and over 49 million workers were absent from work for at least four days due to occupational accidents in 2008 [12,13]. Globally, an estimated 2.3 million work-related deaths occur annually, and the economic cost of work-related injury and illness is estimated at 4% of the world's GDP (Gross Domestic Product) [12,13]. Furthermore, about 2.9 billion workers globally are estimated to be at risk at work, and about 3.5 years of healthy life are lost per 1000 workers globally. Figures of work-related injuries and deaths in the informal sector alone are unavailable. E-waste recycling industry is a young rapidly growing industry. It has created many employment opportunities; affordable access to electronics and parts used for repairs; a continuous supply of raw materials to manufacturers without further exploration of natural resources; and conservation of natural resources and energy required to manufacture new electronics from virgin resources [14]. Informal recycling involves labor-intensive manual dismantling, isolation of materials, open burning of plastics from electronics, heating of circuit boards, use of toxic acid baths for metal recovery as practiced in Asia, and open dump disposal [15,16]. These unsafe recycling techniques are used to recover valuable materials without or with very little technology to minimise exposure, thus allowing the emission of dangerous chemicals. Occupational safety and environmental protection are clearly not prioritised.

Studies have shown that exposure to the mixture of chemicals emitted during e-waste processing is harmful to human health and induces adverse effects including skin disease, under-development of the brain in children [17], damage to the nervous system, malfunctioning of the kidneys, respiratory problems, endocrine disruption, adverse pregnancy and birth outcomes, and poor health burden heritage perpetuated through the mother-to-child etc. [2,18,19]. These health problems are most evident when there is direct occupational exposure like in the case of informal e-waste workers. Despite the risks associated with informal e-waste recycling, there is generally low awareness of the environmental and health risks associated with informal recycling of e-waste, even among e-waste workers themselves [2,15,19,20]. There is a need for the e-waste workers to understand the integral link between their occupation and their health. As a result of international attention to the negative impacts of e-waste activities on the environment and human health [21], Nigeria is a signatory to international treaties (such as the Basel convention) [22] and has national legislations regulating import and management of e-waste in Nigeria [23,24]. Unfortunately, the enforcement of these legislations are weak.

In 2014, Nigeria generated about 219 kilo tonnes of e-waste [1], which is largely recycled by the informal sector [25]. In 2005, an estimated 60,000 metric tonnes of used or scrap computers were imported and about 25–75% of these were non-functional [26, 27]. There is limited attention and information on informal e-waste workers' awareness of the risks inherent in unsafe recycling of e-waste and their work conditions in Nigeria. This poses a challenge to policy makers to design effectively environmentally sound e-waste management strategies, or tailor made intervention programmes for the reduction/prevention of the negative health effects of informal e-waste recycling.

If the level of knowledge correlates with practice and attitude, increasing knowledge of the workers may decrease risky practices; suggesting that a bottom-up approach in tackling the negative effects of e-waste recycling may be an effective strategy to improve the workers' condition. Considering the health risks of exposure to e-waste chemicals, this study therefore aims to answer the following questions:

1. To what extent are informal e-waste workers in Nigeria aware of health risks inherent in their daily jobs?
2. Are workers in other job types (job designations) in the informal sector more aware of their occupational health risks compared with e-waste workers?
3. What factors influence their awareness level across various job types?
4. What factors contribute to the difference in the awareness level across various job designations?

In this study, awareness was assessed by measuring the workers' knowledge, attitude and practices (KAP) on health risks inherent in their daily jobs. We assessed awareness level by using dedicated KAP questions.

2.2. Methods

2.2.1. Study Location

The study was conducted in three study locations/cities (Ibadan, Lagos, and Aba) in Nigeria. The three locations are among the large cities where e-waste is recycled. Ibadan (in Oyo State) and Lagos are located in the South-West and Aba (in Abia State) is located in the South-East geopolitical zones of the country [25]. Figure 2.1 presents a map of Nigeria showing the study locations.

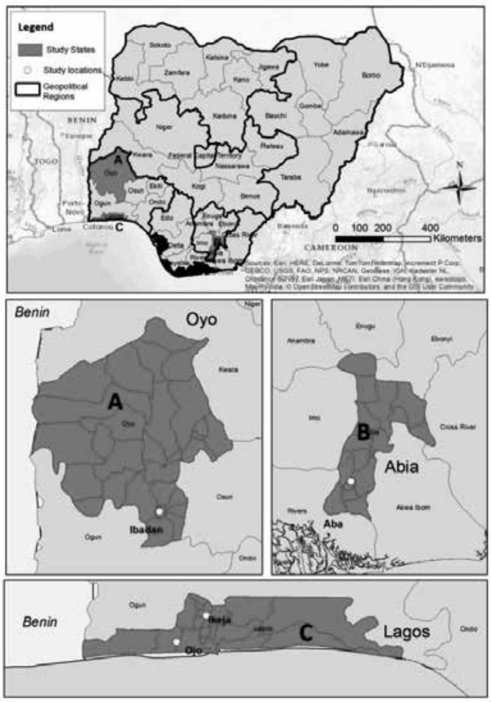

Figure 2.1. Map of Nigeria showing the Study Locations [28].

2.2.2 Study Design

A comparative cross-sectional study design was adopted to gain insight into the awareness level of e-waste workers compared with a similar occupational group in the informal sector in Nigeria. For this study we selected butchers as a control group for the comparison in each study location, because like e-waste workers, butchers constitute a male dominated profession of a comparable socio-economic status in the informal sector, although, a small part of the meat sector is regulated by the government, it is largely an informal sector. Moreover, butchers are also engaged in small-scale enterprises. They make a living from slaughtering and selling meat in abattoirs and markets within the city. Their work involves contact with live animals, their carcasses, blood and body fluids. The e-waste workers were split into two job designations (repairers and dismantlers). The repairers repair or refurbish electronics, while the dismantlers collect/scavenge, dismantle, and burn e-waste to recover valuable materials.

A multi-stage sampling technique was used to select a minimum of 74 e-waste workers and 74 butchers from each study location. The minimum sample size calculated for both groups was 444 (including adjustment for 10% non-response rate). At each study location, there were a couple of areas where e-waste is recycled, of which two major e-waste recycling areas were selected. For Lagos the areas included the computer village Ikeja and the Alaba international market. In Aba, the shopping centre and Cemetery and Jubilee road/St Michael's road areas were selected, while in Ibadan the Ogunpa and Queens Cinema areas were randomly selected. In each selected study area, two sampling sites were randomly selected in order to ensure sufficient samples for the required sample size. Each sampling site comprised of hundreds of units/clusters/shops where e-waste is either repaired/refurbished or dismantled/recycled. At each sampling site, systematic sampling was used to select the recycling units. The participants were selected from the recycling units to ensure that the selected participants are a representative sample of the selected area. Regarding the butchers, they were selected from Oke Oba Abattoir Agege in Lagos, Bodija market in Ibadan, and in Aba, Waterside cattle/Nsulu markets were selected. Figure 2.2 presents a schematic diagram of the sample selection.

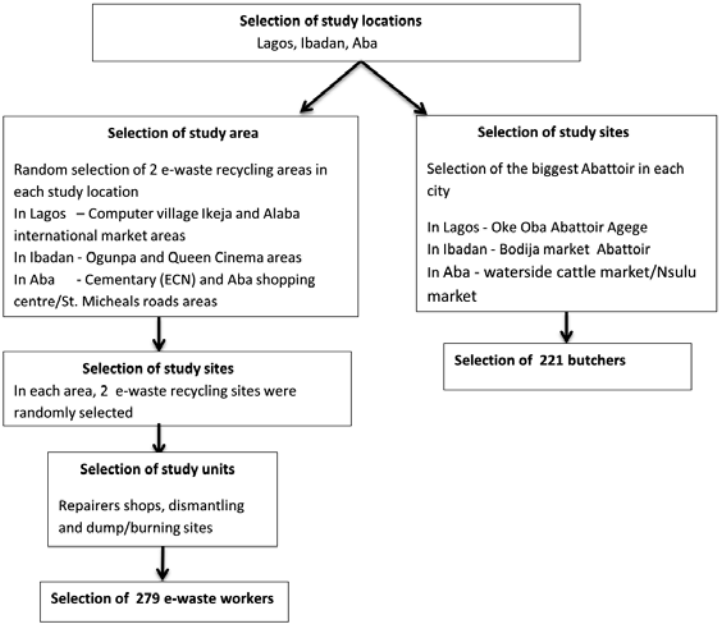

Figure 2.2. Flow diagram for Selection of Participants.

2.2.3. Data Collection

A semi-structured interviewer-administered questionnaire containing open- and closed-ended questions (see Supplementary Materials) was used to obtain information from the respondents between May and October 2015. One week prior to the actual data collection period, the questionnaire was pre-tested at an area different from the selected sampling areas and the questions were modified based on the experiences gained during the pre-test. Daily monitoring and evaluation was carried out to ensure accurate data collection. The workers were interviewed on their socio-demographic backgrounds, occupational history, knowledge, attitude, and work practices (KAP) to assess their awareness level.

2.2.4. Data Analysis

Prior to data analysis, all questionnaires were reviewed for completion and accuracy and compiled in a database. The workers' knowledge on potential health risk as a result of their jobs was assessed by using five questions regarding knowledge of e-waste chemicals, their effects on health, transmission routes, likely health problems as a result of the job, and Personal Protective Equipment (PPE) needed for their jobs. For this study, gloves, work shoes/boots, nose masks (or cloth handkerchiefs improvised as nose mask), any form of head cover, safety glasses/eye protection, ear plugs and coverall/protective work clothes were considered as PPE. Similarly, attitude related to health risks at work was assessed using three questions concerning the workers' perception of injuries at work, sicknesses that resulted in absence from work, perception (i.e., concerns about work) of the workers of their health, and their major challenges and concern while at work. Safety practices were assessed using five questions on the use of PPE, laundering of PPE at home, washing hands before eating while at work, change of work clothes after work, shower after the day's work before going home, and carrying heavy loads at work. Each right and wrong/I don't know response was given a score of 1 and 0, respectively for close-ended questions, but a maximum score of 2 was given for correct responses to open-ended (unprompted) questions. The scores were converted to a 1-to-10-point scale.

To evaluate the differences in the mean knowledge, attitudes and practices scores between job designations, a series of one-way ANOVA (for categorical variables) and linear regressions (for continuous variables) were run after checking that skewness and kurtosis satisfied the assumption of normality with values less than I2.0I and I9.0I respectively [29]. The explanatory variables tested were job designation, location, migration status, education, worker's position in the business, use of PPE, age, and number of years of work experience. The factors that were significant and not strongly collinear to other explanatory variable were selected for further analysis. To get a deeper understanding of the nature of the significant differences, series of two-way ANOVA were run always with job designation as the first factor (given the prime interest in the effects of e-waste workers vs. butchers) and the additional selected variables as second factor. Bonferroni post-hoc tests were included to interpret the significant main effects. All analyses were performed using SPSS version 23.0. In all cases, a *p*-value < 0.05 was considered to be statistically significant.

2.2.5. Ethical Considerations

Ethical approval was obtained from the University of Ibadan/University College Hospital Ethical Review Board (No. UI/EC/15/0096). Verbal and written consent of the workers was obtained at the start of the interview, after explaining to the workers their full rights to refuse and to withdraw at any time during the interview. To ensure that the participant remains anonymous each questionnaire was coded with number identifiers. They were also assured that the data will not be used for other purposes than for scientific reasons and for the development of safety promotion programs for the sector. Permission to conduct the study was also obtained from the butchers' union at each abattoir/market and from association of second-hand electronics dealers at each study site.

2.3. Results

2.3.1. Socio-Demographic and Occupational Characteristics of the Respondents

A total of 279 e-waste workers (55% repairers and 45% dismantlers) and 221 butchers were interviewed. The e-waste workers were younger with a mean age of 30 ± 9 years (repairers 32 ± 8, and dismantlers 29 ± 9) compared to the butchers with a mean age of 40 ± 11 years. Years of work experience ranged from 1 to 32 years for e-waste workers and 1–45 years for butchers. Most of them (98% of the e-waste workers and 82% of the butchers) worked six days a week, and the mean number of working hours per day was 9 ± 2 h for e-waste workers, and 9 ± 3 h for the butchers. A majority (89% of e-waste workers and 93% of the butchers) of the respondents were permanent workers in their profession. Before starting the work, 81% of the e-waste workers and 76% of butchers had at least some form of training, although most (98% of e-waste workers and 99.5% of butchers) of the training was on-the-job training and 88% of e-waste workers and 100% of the butchers got all their training from their employer/senior apprentice. The descriptive statistics associated with the knowledge, attitude, and practice scores of the participants across job designations and other variables are reported in Table 2.1.

Table 2.1. Knowledge, Attitude, and Practice Mean Scores by Job Designation, Location, Job Position, use of Personal Protective Equipment (PPE), and Education.

Predicted Variables		Knowledge Score	Attitude Score	Practice Score
		Mean ± SD	Mean ± SD	
Job designation	Repairers	2.6 ± 1.2	3.02 ± 1.13	4.6 ± 1.35
	Dismantlers	3.7 ± 1.8	3.6 ± 1.66	5.8 ± 1.63
	Butchers	5.9 ± 1.2	3.67 ± 1.68	6.73 ± 1.6
Location	Ibadan	3.9 ± 1.7	3.11 ± 1.24	5.8 ± 1.9
	Lagos	4 ± 2.1	3.5 ± 1.61	5.5 ± 1.6
	Aba	5.2 ± 2.0	3.78 ± 1.70	6.2 ± 1.8
Job position in business	Business owners	2.6 ± 1.2	3.53 ± 1.58	5.9 ± 1.8
	Workers in family business	3.5 ± 2.1	3.56 ± 1.66	6.4 ± 1.6
	Employees/apprentices	2.4 ± 1.2	3.25 ± 1.43	5.6 ± 1.8
Use of PPE	No	3.92 ± 2.11	3.4 ± 1.51	5 ± 1.4
	Yes	5.13 ± 1.56	3.57 ± 1.64	7.5 ± 1.2
Education	No formal education	5.2 ± 1.8	3.5 ± 1.5	6.5 ± 1.9
	Primary	5.2 ± 1.8	3.66 ± 1.78	6.5 ± 1.7
	Secondary	3.9 ± 2.0	3.36 ± 1.42	5.5 ± 1.7
	Post-Secondary	2.9 ± 1.5	3.37 ± 1.66	5.3 ± 1.2

2.3.2. Assessment of Knowledge on Occupational Health Risk

The majority (88%) of e-waste workers (repairers 95%, dismantlers 79%) were unable to mention at least one chemical present in e-waste, and were unaware that e-waste contains hazardous chemicals which could harm their health, while none (0%) of the butchers was unaware that the materials from the animals could pose a health risk. Only 43% of the e-waste workers (37% repairers and 50% dismantlers) and 59% of butchers could mention at least one route of exposure. Only 43% of e-waste workers (34% repairers, 53% dismantlers) and 70% of butchers could mention at least one PPE needed for their job. The majority (77%) of the e-waste workers (82% repairers and 76% dismantlers) and 74% of the butchers did not know the likely illnesses they can contract as a result of their jobs. Overall 70% of the e-waste workers and 78% of the butchers did not think that the substances they are exposed to at work can pose any health risk. In addition, they did not think that they can get ill from their jobs, but from other sources unrelated to their work or work environment. Overall, only 12% of the e-waste workers (repairers 3%, dismantlers 24%) compared with 76% of the butchers had a total score of >5 and were categorized as having good knowledge of their occupational health risk. The mean knowledge scores of the different job designations were repairers 2.6 ± 1.2, dismantlers 3.7 ± 1.8, and butchers 5.8 ± 1.2, reflecting that the butchers had a much better knowledge about the health risks their jobs poses. The mean knowledge scores were significantly different (F (2497) = 269.582, p = 0.000, η^2 = 0.520; indicating that 52% of the variation in knowledge score was explained by job designation) (see Tables 2.1 and 2.2). There was more variation among the dismantlers compared to the other work groups with repairers showing the least variability.

Table 2.2. One-Way ANOVA output for the Knowledge, Attitude, and Practice scores on a 1–10 point scale.

Variable	Knowledge Score	Attitude Score	Practice Score
Job designation	F (2497) = 269.582 *p* = 0.000 η^2 = 0.520	F (2497) = 8.878 *p* = 0.000 η^2 = 0.034	F (2497) = 88.261 *p* = 0.000 η^2 = 0.262
State/Location	F (2497) = 21.928 *p* = 0.000 η^2 = 0.081	F (2497) = 7.715 *p* = 0.001 η^2 = 0.030	F (2497) = 6.045 *p* = 0.003 η^2 = 0.024
Migration status	F (1498) = 15.277 *p* = 0.000 η^2 = 0.030	F (1498) = 0.054 *p* = 0.817 η^2 = 0.000	F (1498) = 12.822 *p* = 0.000 η^2 = 0.025
Education	F (3496) = 26.886 *p* = 0.000 η^2 = 0.140	F (3496) = 1.125 *p* = 0.338 η^2 = 0.007	F (3496) = 15.678 *p* = 0.000 η^2 = 0.087
Position in Business	F (2497) = 4.039 *p* = 0.010 η^2 = 0.018	F (2497) = 1.688 *p* = 0.186 η^2 = 0.007	F (2497) = 2.965 *p* = 0.052 η^2 = 0.012
Use of PPE	F (1498) = 143.406 *p* = 0.000 η^2 = 0.080	F (1498) = 1.350 *p* = 0.246 η^2 = 0.003	F (1498) = 377.618 *p* = 0.000 η^2 = 0.431
Age (continuous)	F (1498) = 52.459 *p* = 0.000 R = 0.309	F (1498) = 0.257 *p* = 0.612 R = 0.023	F (1498) = 16.523 *p* = 0.000 R = 0.179
Years of work experience (continuous)	F (1498) = 6.937 *p* = 0.009 η^2 = R = 0.117	F (1498) = 0.003 *p* = 0.960 η^2 = R = 0.002	F (1498) = 0.829 *p* = 0.363 η^2 = R = 0.041

Partial Eta squared (η^2) = Effect size.

2.3.3. Factors that Influence the Knowledge Scores of the Workers

The multicollinearity analysis revealed a weak correlation between job designation and ethnicity, migration status, position in business, and use of Personal Protective Equipment (PPE); also, there was a weak correlation between age and years of work experience. However, a strong correlation was found between job designation and education, the repairers were more educated than the other groups. In addition, there was a strong correlation between location and ethnicity; each location had a particular dominant ethnic group.

To understand the factors that could influence the scores across the job designations (which is the prime interest), a series of one-way ANOVA (for categorical variables) and linear regressions (for continuous variables) were run. Job designation might contribute to a worker's awareness level of occupational health risk, but that effect may differ across locations, educational status, age, job position in a business and use of PPE (see Table 2.2). To evaluate the nature of the significant differences in the mean scores, series of two-way ANOVA were run always with job designation as the first factor (given the prime interest in the effects of e-waste workers vs. butchers) and the additional selected explanatory (predicted) variables as second factor.

Table 2.3 presents the results of the main effects of job designation, the other explanatory variables (factor-i), and the interaction effects between the job designations and the other explanatory variables on the knowledge score. A visual depiction of the significant interaction effects of job designation and predicted variables on the mean score of knowledge are presented in Figures 2.3–2.5.

Table 2.3. *F*-values of the Two-Way ANOVA for the Knowledge Score

Factor-i	**Job Designation (η^2)**	**Factor-i (η^2)**	**Job#Factor-i (η^2)**
State/Location	312.474 (0.560) ***	31.724 (0.114) ***	8.605 (0.066) ***
Migration status	195.293 (0.442) ***	0.000 (0.000)	0.375 (0.002)
Education	46.839 (0.161) ***	0.968 (0.006)	1.043 (0.011)
Job Position	73.802 (0.231) ***	1.344 (0.005)	7.835 (0.060) ***
Use of PPE	144.044 (0.368) ***	1.854 (0.004)	13.626 (0.052) ***
Age (ANCOVA)	20.421 (0.076) ***	1.082 (0.002)	0.248 (0.001)
Years of work experience (ANCOVA)	109.069 (0.306) ***	1.34 5 (0.003)	1.761 (0.007)

*** $p < 0.001$, ** $p < 0.01$,* $p < 0.05$, Partial Eta Squared = η^2, Interaction = #.

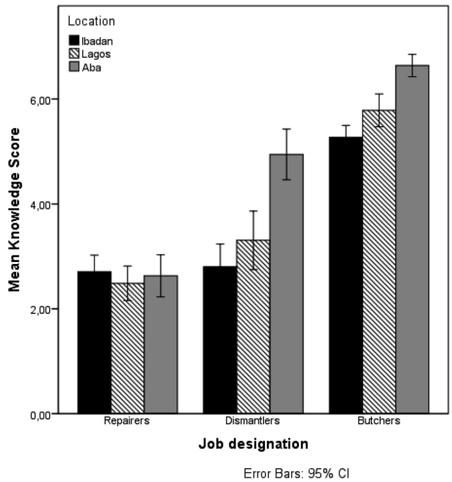

Figure 2.3. Mean Knowledge Score by Job Designation and Location.

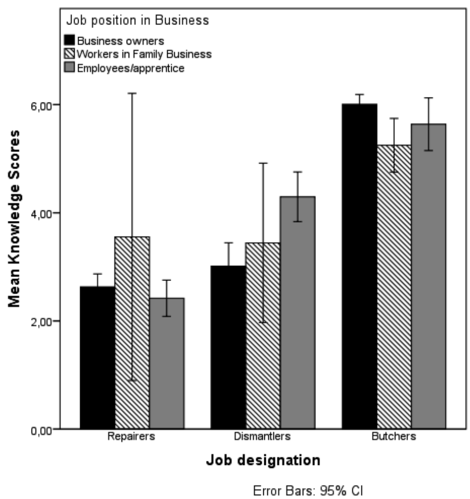

Figure 2.4. Mean Knowledge Score by Job Designation and Job Position in Business.

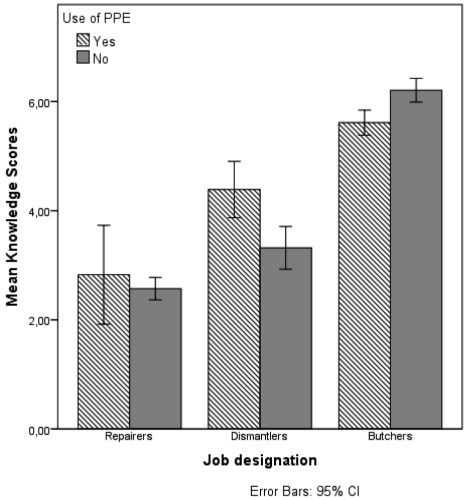

Figure 2.5. Mean Knowledge Score by Job Designation and use of PPE.

As Figure 2.3 shows, the interaction effect between job designation and location on knowledge score, the interaction effects may be explained from the high knowledge score of dismantlers in Aba. Figures 2.4 shows that the effect of job designation on the knowledge also depends on the worker's position in business. Particularly for dismantlers there is a large difference in the knowledge score of the employees/apprentices compared to the business owners. Among the repairers and butchers, there is no difference in the mean knowledge scores of the employees/apprentices compared to the business owners. There is clearly more variability in the mean knowledge scores of people working in family businesses. As Figure 2.5 shows, the use of PPE is particularly related to higher knowledge scores for dismantlers, but not for the other two job designations.

2.3.4. Assessment of Attitude towards Health and Safety at Work

The workers' opinions reflect their attitudes towards their health as a result of their job. About 90% of the e-waste workers (95% repairers, 84% dismantlers) and 84% of the butchers did not perceive injury at work serious enough to worry about. Only about 17% of e-waste workers (14% repairers, 19% dismantlers) and 18% of the butchers believed that the sicknesses they suffered in the last 12 months could be as a result of their jobs. About 70% of the workers did not worry about their health as a result of their jobs, and the majority (86% repairers, 88% dismantlers, 86% butchers) of them felt very good about their health. Despite the dangerous work conditions, only about 4% of the e-waste workers (7% repairers, 10% dismantlers) and 23% of the butchers mentioned worrying about their health. Regarding their major concerns, the majority (51%) of e-waste workers (54% repairers, 47% dismantlers) and 48% of the butchers reported that their major concern is finance (making more money); only 4% of the repairers, 3% of the dismantlers, and 23% of the butchers mentioned health as their major concern. The mean attitude scores across the three job designations were significantly different (F (2497) = 8.878, p = 0.000, η^2 = 0.034; explaining 3.4% of the variation). The mean attitude scores of the participants were: repairers 3.0 ± 1.1, dismantlers 3.6 ± 1.7, and butchers 3.7 ± 1.7; reflecting that the butchers had a better attitude towards their health in relation to their jobs (see Tables 2.1 and 2.2). Factors that influence the attitude scores of the workers were determined by following the steps explained in Section 3.3. Table 2.4 presents the results of the main effects of job designation, the other explanatory variables (factor-i), and the interaction effects between the job designations and the other explanatory variables on the attitude score. A visual depiction of the significant interaction effects of job designation and predicted variables on the mean score of attitude is presented in Figure 2.6.

Table 2.4. *F*-values of the Two-Way ANOVA for the Attitude score.

Factor-i	Job Designation (η^2)	Factor-i (η^2)	Job#Factor-i (η^2)
State/Location	10.789 (0.042) ***	3.165 (0.013) *	9.721 (0.073) ***
Migration status	10.202 (0.040) ***	0.199 (0.000)	1.284 (0.005)
Education	4.860 (0.019) **	2.543 (0.015)	3.025 (0.030) **
Job Position	1.363 (0.006)	1.213 (0.005)	0.217 (0.002)
Use of PPE	3.334 (0.013) **	0.355 (0.001)	0.655 (0.003)
Age (ANCOVA)	0.779 (0.003)	0.165 (0.000)	0.028 (0.000)
Years of work experience (ANCOVA)	6.135 (0.024) **	0.016 (0.000)	0.974 (0.004)

*** p < 0.001, ** p < 0.01,* p < 0.05, Partial Eta Squared = η^2, Interaction = #.

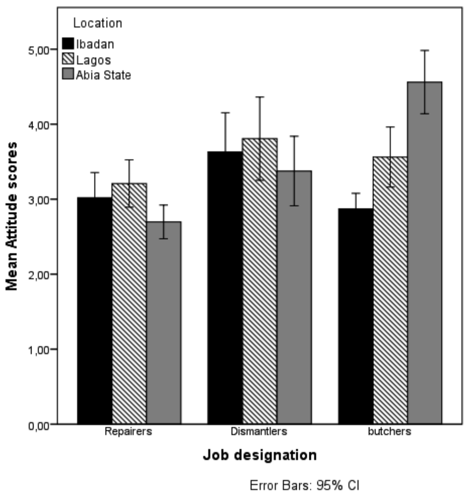

Figure 2.6. Mean Attitude Scores by Job Designation and Location.

2.3.5. Assessment of Work Practices

Only 18% of the e-waste workers (7% repairers, 32% dismantlers) and 55% of the butchers used at least one type of PPE either most of the time or occasionally. The types of PPE commonly used by e-waste workers were gloves (13%), nose masks (7%), and boots (8%). Butchers used gloves (10%), nose masks (8%), boots (12%), overalls (20%), and head covers (15%). None of the workers used safety glasses, ear plugs or helmets. About 45% of the e-waste workers (repairers 49%, dismantlers 40%) and 60% of the butchers took their work clothing or shoes home for laundering. The majority (68.5%) of the e-waste workers (63% repairers, 75% dismantlers) and 74% of the butchers washed their hands before eating while at work. Many workers (66% e-waste workers, 42% butchers) carried heavy loads at work and the majority (55% e-waste workers, 73.3% butchers) reported uncomfortable (bent/twisted upper body) work position at work. The mean practice scores across the three job designations were significantly different (F (2497) = 88.261, p = 0.000, η^2 = 0.262); explaining 26.2% of the variation. The mean practice scores of the participants were: repairers 4.6 ± 1.35, dismantlers 5.8 ± 1.63, and butchers 6.73 ± 1.6. This implies that the butchers had a safer work practice compared to the e-waste workers (Tables 2.1 and 2.2). Overall, only 32% of the e-waste workers (repairers 16%, dismantlers 50%) compared to 70% of the butchers had a total score of >5 and were categorized as having a safe practice. Factors that influence the practice scores of the workers were determined by following the steps explained in Section 3.3. Table 2.5 presents the results of the main effects of job designation, the other explanatory variables (factor-i), and the interaction effects between the job designations and the other explanatory variables on the mean practice scores. A visual depiction of the significant interaction effects of job designation and predicted variables on the mean practice scores are presented in Figures 2.7 and 2.8.

Table 2.5. *F*-values of the Two-Way ANOVA for the Practice Score.

Factor-i	Job designation (η^2)	Factor-i (η^2)	Job#Factor-i (η^2)
State/Location	312.474 (0.560) ***	31.724 (0.114) ***	8.605 (0.066) ***
Migration status	195.293 (0.442) ***	0.000 (0.000)	0.375 (0.002)
Education	46.839 (0.161) ***	0.968 (0.006)	1.043 (0.011)
Job Position	73.802 (0.231) ***	1.344 (0.005)	7.835 (0.060) ***
Use of PPE	144.044 (0.368) ***	1.854 (0.004)	13.626 (0.052) ***
Age (ANCOVA)	20.421 (0.076) ***	1.082 (0.002)	0.248 (0.001)
Years of work experience (ANCOVA)	109.069 (0.306) ***	1.345 (0.003)	1.761 (0.007)

*** p < 0.001, ** p < 0.01,* p < 0.05, Partial Eta Squared = η^2, Interaction = #.

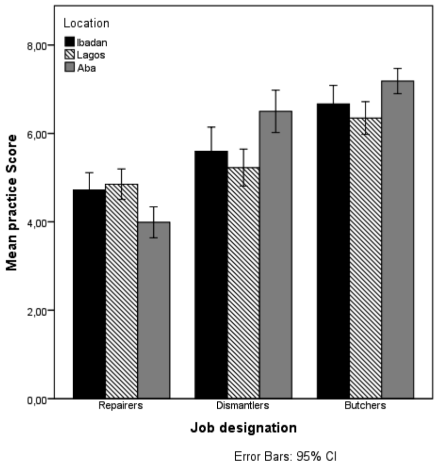

Figure 2.7. Mean Practice Scores by Job designation and Location.

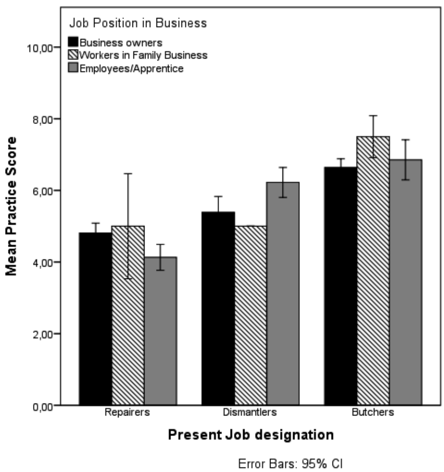

Figure 2.8. Mean Practice Scores by Job Designation and Job Position in Business.

2.4. Discussion

As far as we are aware, this is the first study that conducted detailed analyses of the Knowledge, Attitude, and Practice (KAP) of e-waste workers in the informal sector in Nigeria. Our study population showed overall poor knowledge of occupational health risks among e-waste workers compared with butchers. Overall, the occupational health risk awareness level is dependent on job designation, location and position in the business, especially among dismantlers. The strengths of this study are its focus on the informal e-waste recycling sector which is not commonly studied, assessment of the occupational health risk awareness level (knowledge, attitudes and practices) of the workers, comparison of the health risk awareness level of e-waste workers with a control group (butchers) of the same socio-economic status, use of the same research tools (adapted for butchers) to access the different work groups, large sample size, distribution of respondents across three major cities in two different geopolitical zones in Nigeria, and the use of both closed and open ended questions for the KAP assessment. However, the accuracy of the data is dependent on the ability of the respondents to be open to give the correct response irrespective of fear of government actions as a result of their responses.

The three job designations had significantly different mean knowledge, attitude, and practice scores; showing that the groups are different from each other and are from different populations. Despite the international awareness of the negative impacts of e-waste activities on the environment and human health, e-waste workers showed overall poorer knowledge (88%), more negative attitude (74%), and more unsafe practices (58%) compared to butchers on the potential health risks inherent in their jobs. However, none of the groups had remarkable knowledge, attitude or practice. This confirms the statements made by Widmer *et al*. [30], Borthakur [20] and Lundgren [2] who claimed that most of the participants in the informal e-waste recycling sector are not aware of environmental and health risks and do not know of better practices. Although the repairers were better educated than the dismantlers, the dismantlers were significantly more aware of the likelihood of health risks associated with their jobs. This could be due to the obviously risky work practices, and unhygienic work environment in which they work, which is contrary to the work environment of repairers although some of the repairers work with printer and photocopier toners which are considered dangerous [31]. Similarly, the general public is unaware of the dangers inherent in informal e-waste recycling. The majority of the people in India [20,32,33] and in Onitsha, Nigeria [34] were not aware of the harmful content of e-waste. In contrast, a higher proportion of informal workers in other fields, such as municipal solid waste workers (61%) in Ethiopia [35], and 63% of the butchers in Ibadan Nigeria [36] were reported to be more aware of the health risk inherent in their jobs, although awareness did not translate to good practice. However, in Aba, Nigeria, 82% of the scavengers are not aware of the dangers inherent to their jobs [36].

Regarding likely health problems as a result of their jobs, the majority (77%) of e-waste workers did not think that their jobs pose any health problem. These workers stated that there are many factors that can cause illness. Furthermore, only 3.5% of the e-waste workers and 23% of the butchers were concerned about their health as a result of their jobs. This shows that most workers in the informal sector work mainly for economic benefits. This is in agreement with the results of a study in Aba by Nzeadibe *et al*. which stated that 82% of the scavengers do not believe that there are health problems related to their jobs [37].

The significant effects of the location on the mean scores could be caused by the fact that each geographic location is dominated by one major ethnic group (this is highly correlated with location) which in turn influences their attitude/believes and practices. The location effect suggests that any health intervention should consider ethnicity and location. Furthermore, most the dismantlers and repairers in our study are from two different regions of the country respectively. This is confirmed by studies which stated that most of the dismantlers in Ghana [38] and Nigeria [25] are from a particular region of the country. In our study, employees and apprentices seem to have better knowledge and practices than their employers or business owners, most likely because the employees are more involved in doing the actual work and are newer in the business; they are more likely to identify health changes they experience in their new pursuit, while the business owners handle other aspects of the businesses and are no longer aware of health changes they probably experienced when they started the business. Surprisingly, there was no significant interaction effect of job designation and education on the knowledge scores, but there were interaction effects of job designation and education on attitude and practice scores. This agrees with the study by Asampong *et al*. (2015) [38], that states that lack of formal education of e-waste workers in Ghana influenced their attitude and practices.

When considering the results reported here, it is likely that the results obtained are affected by the nature of the responses given by the respondents. First of all, the need for awareness as reported by dismantlers seemed to have suddenly dawned on them during the interview, whereby the interview seems to have acted as a sudden wake-up call for most of these workers; they indeed confessed that this was the first time they were being interviewed about their jobs in relation to their health Some of the workers were also in doubt whether their responses would be used against them. This doubt is induced by the fact that in recent times, the Nigerian government has put in place stricter regulations on importation of used electronics [39]. Given that these effects may have overestimated the awareness of dismantlers particularly, it re-emphasizes the low awareness levels of people working in the informal e-waste sector, e.g. compared to butchers.

The workers' knowledge, attitude, and practice levels is dependent on the interaction effects between job designation and the other explanatory variables (location/ethnicity, position in business and use of Personal Protective Equipment (PPE) showing that these factors are very much intertwined. Therefore to plan for any health awareness/education programme for the e-waste workers or other workers in the informal sector, these factors should be considered. We anticipate that this work will help decision makers to understand the informal setting, this group of workers, and also to contribute to change in redesigning more effective e-waste management strategies/plans considering the realities of the e-waste workers in Nigeria.

2.4.1. Social-Cultural Context of the Research Setting

The workers in the informal sector/economy form informal associations/networks, which are usually formed by a group of people who are informally bound together by mutual needs or common interest, and membership is voluntary. They establish their own leadership, set rules that govern them, and they meet regularly. These associations usually provide them with emotional and financial support, as well as sharing of knowledge. These associations also give them a sense of belonging [40,41]. The strength of informal associations is that members feel the need to belong to the association, therefore the associations are sustained. In Nigeria informal associations are usually formed along ethnic lines and common business interest. These associations have proved to operate efficiently without any formal support. However, they often work in cross-purposes with formal sector/economy [40]. The formal sector, international organizations and academics do not understand the dynamics of African informal economy, so they tend to represent it in terms of criminality or cultural dysfunction, therefore they treat the informal sector as structurally inadequate and irrelevant [40].

It is important to note that occupational exposure to health risk and accidents occur in both formal and informal settings, and those occurrences could be due to human error [42,43], lack of risk assessment and risk management. However in formal and complex settings, there are organizational occupational safety and health (OS&H) programmes and policies put in place to minimize exposure to health risks in work places but in the informal settings, OS&H are nonexistent, mainly because during the formulation of the policies and regulations, the informal sector is not considered or involved, which leads to difficulties in implementation of government policies and regulations. To improve OS&H in the informal sector, formal institutions such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) should appreciate, understand and work with the informal associations. The enforcement agencies must be seen not to be antagonistic so as to influence the workers in the informal sector to align with government policies. Although the informal associations are self-organizing, they can be encouraged to abide by government regulations, if they perceive that they are appreciated by the enforcement agencies. NESREA in combination with Ministry of Health can work together with the informal associations to develop effective grassroot communication methods which will improve the workers' health risk knowledge and work practices.

2.5. Conclusions

Informal workers often underestimate the health risks associated with their jobs. It is important that workers in the informal settings are aware of the potential health risks peculiar to their jobs and the safety measures to be undertaken. One way to improve the awareness level is for formal institutions to work with the informal associations to communicate the health risks and OS&H associated with their jobs. Our findings provide a scientific basis crucial to devising appropriate OS&H intervention for e-waste workers and other workers in the informal sector. Health risk awareness level of the e-waste workers were significantly lower compared with their counterparts (butchers) in the same informal sector. Since the level of knowledge correlated with practice, increasing the workers' health risk knowledge may decrease risky work practices; suggesting that a bottom-up approach in reducing health risk practices in the informal sector may be more effective. However, to implement health risk awareness programmes in the informal sector, it should be borne in mind that the approach may differ depending on the type of job performed, location, and workers' position in the business.

Supplementary Materials: The following are available online at www.mdpi.com/link, Table S2.1: Socio-demographic characteristics of all the informal workers, Table S2.2: Knowledge of work health risk, Table S2.3: Healthy work Attitude at work, Table S2.4: Healthy work Practice.

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Supplementary Information for Chapter 2

Table 2.1: Socio-Demographic Characteristics of all the Informal Workers

Demographic characteristics		**Job designation**		
		Repairers=153n (%)	**Dismantlers=126 n(%)**	**Butchers=221**
Location	Lagos	67 (43.8)	44 (34.9)	73 (33)
	Ibadan	48 (31.4)	42 (33.3)	74(33.5)
	Aba	38 (24.8)	40 (31.7)	74(33.5)
Age	30 years or less	79 (51.6)	81 (64.3)	55(25)
	More than 30 years	74 (48.4)	45 (35.7)	166(75)
Education	No formal Education	0(0)	12 (9.5)	40(18)
	Primary	8 (5.2)	23 (18.3)	97(44)
	Secondary	105 (68.6)	85 (67.5)	79(36)
	Post-secondary	40 (26.1)	6 (4.8)	5(2)
Training	Yes	125 (81.7)	101 (80.2)	157(71)
	No	28 (18.3)	25 (19.8)	64(29)
Training type received	On-the-job training	148 (96.7)	126 (100)	219(99.1)
	Training by an expert	5 (3.3)	0 (0)	2(0.9)
Kind of employment	Permanent	136 (88.9)	112 (88.9)	206(93.2)
	Temporary	17 (11.1)	14 (11.1)	15(6.8)
Position in business	Business owner	98 (64.1)	56 (44.4)	176(79.6)
	Employee/Apprentice	50 (32.7)	60 (47.6)	27(12.2)
	Family business	5 (3.3)	10 (7.9)	18(8.1)
Years of work experience	1-10 years	115 (75.2)	101 (80.2)	96(43.4)
	More than 10 years	38 (24.8)	25 (19.8)	125(56.6)
Work-hours/day	8 hours or less	48 (31.4)	26 (20.6)	93(42)
	More than 8 hours	105 (68.6)	100 (79.4)	128(58)
Income	N2000 or less	86 (30.8)	84 (30.1)	116(52.5)
	N2001-N5000	36 (12.9)	27 (9.7)	82(37.1)
	More than N5000	31 (11.1)	15 (5.4)	23(10.4)
Use of PPE	Yes	11(7.2)	40 (31.7)	115(52)
	No	142 (92.8)	86 (68.3)	106(48)
Ethnicity	Igbo	73 (47.7)	48 (38.1)	60 (27.1)
	Yoruba	64 (41.8)	47 (37.3)	113 (51.1)
	Hausa	0 (0)	18 (14.3)	29 (13.1)
	Others	16 (10.5)	13 (10.3)	19(8.6)

Table 2.2: Knowledge of Work Health Risk

Knowledge of health risk (scores)	Job designation		
	Repairers (153)	Dismantlers (126)	Butchers=221(100) n(%)
For EW: what type of chemicals come from this second hand electronics during recycling For B: what type of substances come from the animals	7(4.6)	27(21.4)	221 (100))
For EW:Do you think chemicals from second-hand electronics can affect health? For B:Do you think substances from the animals can affect health?	44(28.8)	40(31.7)	49 (22.2)
Which route of exposure(entrance to the body) do you think the chemicals/substances can enter your body?	56(36.6)	63(50)	130 (58.8)
Could you list the Personal Protective Equipment (PPE) you need for your work?	52(34)	67(53.2)	154 (69.7)
What health problems or illnesses do you think can happen due to work environment?	28(18.3)	32(25.4)	99 (44.8)
Knowledge level			
Poor Knowledge	149(97.4)	96(76.2)	54(24.4)
Good knowledge	4(2.6)	30(23.8)	167(75.6)
Knowledge mean score	2.59 ±1.24	3.66±1.82	5.9±1.23

EW=E-waste workers, B=Butchers

Table 2.3 Healthy Work Attitude at Work

Attitude Towards Health and Work (scores)	Repairers (153) n(%)	Dismantlers (126) n(%)	Butchers= 221(100) n(%)
How would you perceive the injury you experience on this job most times			
Serious	7(4.6)	20(15.9)	36 (16.3)
Mild/moderate	146(95.4)	106(84.1)	185 (83.7)
Do you think the sicknesses you had the last 12 months due to your jobs?			
Yes	22(14.4)	24(19)	39 (17.6)
No	75(49)	90(71.4)	123 (55.7)
I don't know	56(36.6)	12(9.5)	59 (26.7)
Do you worry about your health or that of your family due to your work environment?			
No, do not worry	116 (75.8)	80 (63.5)	146 (66.1)
Previously worried, but no longer worried	18 (11.8)	28 (22.2)	59 (26.7)
Little worried	9 (5.9)	6 (4.8)	8 (3.6)
Yes, very worried	10 (6.5)	12 (9.5)	8 (3.6)
What are the major challenges in your business			
Health	6 (3.9)	4 (3.2)	51 (23.1)
Work environment	28 (18.3)	28 (22.2)	31 (14)
Finances	83 (54.2)	59 (46.8)	106 (48)
No response	35 (22.9)	27 (21.4)	41 (18.6)
No challenges	1(0.7)	0(0)	4(1.8)
Attitude score	3.02 ± 1.13	3.6±1.66	3.67±1.68
Poor Attitude(≤5)	124(81)	81(64.3)	139(62.9)
Good Attitude(>5)	29(19)	45(35.7)	82(37.1)

Chapter 3

Prevalence and Injury Patterns Among Electronic Waste Workers In The Informal Sector In Nigeria

Based on article:

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E-waste Workers working without Personal Protective Equipment (PPE)

Photo credit: Chimere May Ohajinwa, 2015

Abstract

Background

Despite the large volume of e-waste recycled informally, the prevalence of work-related injuries among e-waste workers is unknown. Therefore, this study assessed the prevalence, patterns, and factors associated with occupational injuries among e-waste workers in the informal sector in Nigeria.

Methods

This cross-sectional study adopted a multi-stage sampling method to select 279 respondents from three cities (Ibadan, Lagos and Aba) in Nigeria. A questionnaire was used to obtain information on socio-demographics, work practices, and injury occurrences from the respondents in 2015. The data was analysed using descriptive statistics and standard logistic regression.

Results

We found high injury prevalence of 38% and 68% in one-two weeks and six months preceding the study respectively. The most common injuries were cuts (59%). Injuries were mainly caused by sharp objects (77%). The majority (82%) of the injuries occurred on the hands/fingers. Despite the high occurrence of injury, only 18% of the workers use Personal Protective Equipment (PPE) and 51% of those that use PPE got at least an injury in one-two weeks and 88% got at least an injury in six months preceding the study. The factors associated with injury in one-two weeks were job designation and the geographical location, while the factors associated with injury in six months were job designation, geographical location, and age.

Conclusions

There is a high prevalence of injury and low use of PPE among the e-waste workers in Nigeria. Occupational injury can be reduced through health education and safety promotion programmes for e-waste workers.

3.1 Introduction

Electrical and electronic waste (E-waste), also known as Waste Electrical and Electronic Equipment (WEEE), consists of electrical and electronic devices (including all its components such as batteries) that are discarded by the owner as waste without intent of re-use, and are at the end of their useful life[1-4]. The contemporary advancements in technology have led to an exponential demand for electronic equipment and a rapid increase in the rate of e-waste generated in all countries[1]. E-waste is one of the fastest growing municipal waste streams. Globally, an estimated 41.8 million metric tons of e-waste were generated in 2014, and it is estimated to increase to 50 million metric tons by 2018[1]. E-waste contains over 1000 different substances, some of which are harmful substances such as heavy metals (lead, mercury, cadmium, arsenic beryllium) and persistent organic pollutants (like polychlorinated biphenyls and brominated flame retardants). E-waste is chemically and physically different from other forms of general waste, and therefore requires special handling to avoid environmental contamination[4] and health problems[5,6]. About 80% of the e-waste generated are recycled informally in developing countries and it is mostly being disposed together with the general waste stream[7,8,9].

In many developing countries, the demand for contemporary technology has largely been met through the import of used electronic products from developed countries[10]. At the same time, developing countries lack the infrastructure and technology to manage the electronics in an environmentally responsible manner when they reach the end-of-life (i.e when they become e-waste). E-waste is therefore managed/recycled informally under dangerous working conditions, putting human health at risk[6,8,11]. The term 'informal' is often characterized as lacking official governance, regulation, structure and institutionalization, and registeration[12,13]. In the informal sector, most of the workers are self-employed and they work mainly for economic benefits, as e-waste recycling has become an attractive source of employment and income in developing countries[2,12]; with businesses ranging from one-man business to small family-based networks and to large and well organized trading firms[14]. Informal e-waste recycling is the recovery of valuable materials which involves labor-intensive manual dismantling, isolation of materials, and open burning. These processes release hazardous substances during manual dismantling, smelting, burning, and incomplete combustion of e-waste components. Labour standards are not enforced, while work practices are harmful to human health[2,12], and there are limited or no measures to prevent environmental contamination and health problems [2,5,12-14]. However, it is recognized that informal recycling produces purer materials than formal recycling[13].

Nigeria imports the largest volume of new and used electronic and electrical equipment(EEE) in Africa[12,14]. About 50% of electronics used in Nigeria are imported as second-hand (used) electronics. About 25–75% of the imported second-hand computers are non-functional or unrepairable[14,15]. This leads to rapid accumulation of large volumes of e-waste which are recycled informally to recover valuable materials[4,12]. Nigeria generated about 219 kilo tonnes of e-waste in 2014[1], which are largely recycled by the informal sector[14]. Nigeria is a signatory to international treaties (such as Basel Convention)[15] and has national legislation on E-waste management designed to reduce informal recycling of e-waste[14,16], however, the enforcement of the legislation is at its ebb. There is generally low public awareness of the environmental and health risks associated with informal recycling of e-waste even among the e-waste workers[2,14,17]. E-waste workers work without personal protective equipment (PPE), exposing themselves to hazardous substances and occupational injuries which could be exposure routes to hazardous substances[2,18,19].

Despite the high volume of e-waste recycled in Nigeria, there are no publications on the injuries among e-waste workers. As far as we are aware, the only publication on occupational injuries among informal e-waste workers is one qualitative study in Ghana, which studied the health seeking behaviour of the e-waste workers when they are sick or sustain injury at work[19]. The first step to injury prevention is knowing the magnitude of the problem. Therefore, the availability of statistical data on work-related injuries is important[20]. To provide sustainable injury prevention programmes for informal e-waste workers, there is a need to have an understanding of the exposure to hazardous substances via occupational injuries, the use of PPE and the effectiveness of PPE use. This study therefore assessed the prevalence, patterns, and factors associated with occupational injury for e-waste workers in the informal sector in Nigeria.

3.2 Methods

The study was conducted in three study locations/cities (Ibadan, Lagos, and Aba) in Nigeria. Nigeria is grouped into six geopolitical zones. The three locations are among the large cities where e-waste is recycled. Ibadan (in Oyo State) and Lagos are located in the South-Western and Aba (in Abia State) is located in the South-Eastern geopolitical zones of the country respectively[14]. Figure 3.1 presents a map of Nigeria showing the study locations.

A cross-sectional study design was used to gain understanding of prevalence and potential factors associated with occupational injury among informal e-waste workers in Nigeria. A multi-stage random sampling technique was used to select the 279 e-waste workers from the three study locations. The sample size for the study was determined by using the formula for comparison of two means [$n = 2\sigma2 (Z\alpha/2+Z1-\beta)2/(\mu1 - \mu2)2$]. The design of the study was to compare e-waste workers to a control group for some health outcomes; one of the health outcomes considered was occupational injury; but this paper focuses only on the occupational injury among e-waste workers. The sample size calculation gave a minimum of 74 participants in each study location.

$$n = \frac{2\ \sigma2\ (Z\alpha/2+Z1-\beta)2}{(\mu1 - \mu2)2} = 67$$

Where, n = required sample size

$Z\alpha/2$ = Standard normal deviation corresponding to 95% confidence level set at 1.96
$Z1-\beta$ = Standard normal deviation corresponding to 80% statistical power set at 0.84
$\sigma2$ = Standard deviation of the outcome at 19.48[21].
$\mu1$ = Mean Outcome of experimental group at 134.04[21].
$\mu2$ = Mean outcome of control group at 124.95[21].

Adjusting for 10% non-response rate
$nf = n/1 – NR$
Where nf = Adjusted sample size due to attrition.
NR = 10% non-response rate,
$nf = 67/1 – 10\% = 74$ (minimum sample size for each study location)

The e-waste workers were split into two job designation groups (repairers and dismantlers) because their activities are largely different. The repairers are those that repair or refurbish electronics, while the dismantlers comprise of collectors/scavengers, dismantlers, and burners of e-waste to recover valuable materials. Most of the dismantlers are involved in all three activities depending on available jobs. For this study, two major e-waste recycling areas were selected in each study location. In each selected study area, two sampling sites were randomly selected, to ensure sufficient and inclusion of various types/groups of e-waste workers. The sampling sites comprise of hundreds of units/clusters/shops where e-waste is either repaired/refurbished or dismantled/recycled. Systematic random sampling was used to select the sampling units. The participants were selected from the sampling units. These stages of selection were to ensure that the selected participants are a representative of the selected area and to reduce the likelihood of selection bias. The eligibility criteria for selection of the participants included: 1) The participant must be at least 18 years old and 2) must have worked in the informal e-waste recycling sector for at least one year. In Ibadan, Ogunpa and Queens Cinema areas were selected. In Lagos, Computer village Ikeja and Alaba international market were selected. In Aba, Cemetary and Aba shopping centre areas were selected; (Aba shopping centre comprise of St Micheals/Jubilee roads area). Figures 3.1 and 3.2 present the study locations and a schematic diagram of the sample selection respectively.

3.2.1 Data Collection

A semi-structured interviewer administered questionnaire (see supplementary) was used to obtain information from the respondents between May and October 2015. One week prior to the actual data collection period, the questionnaire was pre-tested at an area different from the selected sampling areas and the questions were modified based on the experiences gained during the pre-test. During data collection, regular supportive supervision and discussion among research assistants and supervisors was done on the spot at the end of each day by the investigator to monitor and ensure quality data collection process. The workers were interviewed on their socio-demographic characteristics, work practices, trainings, injuries sustained at work, and other health related questions. Injury was considered as a physical harm or damage to someone's body caused intentionally or unintentionally[22,23]. We also collected information on body pains as a result of their jobs in the last 12 months before the study.

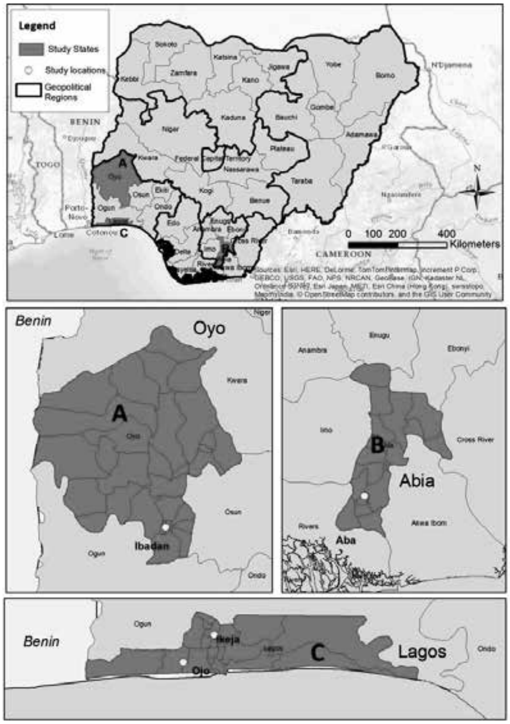

Figure 3.1 Map of Nigeria showing the three Study Locations

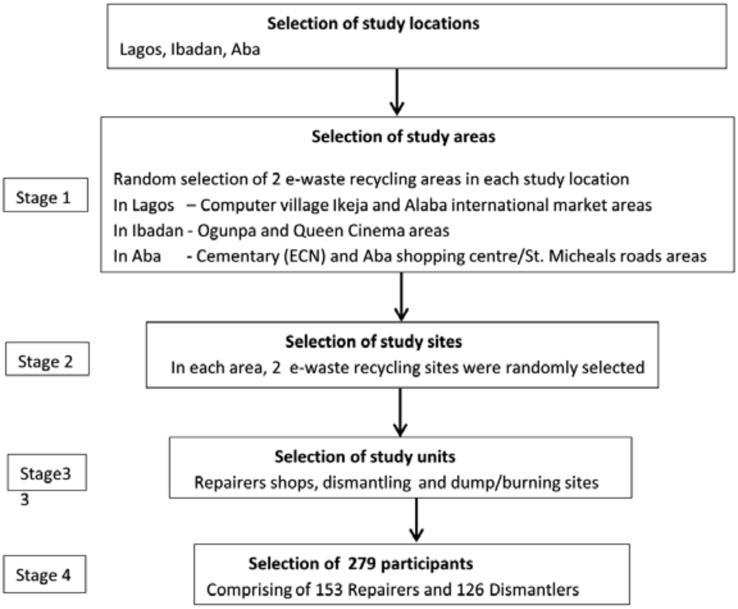

Figure 3.2 Flow Diagram of the Sample Selection

3.2.2. Variable Description

Outcome variables considered were occupational physical and blunt injuries. We also collected information on the body pains they experienced as a result of their job. We asked the participants if they had ever sustained an occupational injury. To get an idea of the frequency of such injuries, we asked whether it had occurred and the number of injuries within the last one-two weeks and six months before the study. Injury occurrence was grouped into: has ever got injury, injury within 6 months, and injury in one-to-two-weeks before the study. Injury occurrence was categorised into Yes=1, No=2. We compared the one-two weeks period with the six months period, because. we expected a recall bias in the six months' timeline compared to the one-two weeks' timeline.

Explanatory variables selected were:- Job designation, location, education, age, position in business, number of work-hours per day, number of work-years(work experience), income, and use of PPE. For this study, gloves, work shoes/boots, nose mask (or cloth handkerchief improvised as nose mask), safety glasses/eye protection, ear plugs and coverall/protective work clothes were considered as Personal Protective Equipment (PPE)[24].

3.2.3. Data Analysis

Prior to data analysis, all questionnaires were reviewed for completion and accuracy and compiled in a database. Incomplete questionnaires were removed. Descriptive statistics (frequencies and percentages) were used to summarise the results. Chi square tests were used to determine associations between injury occurrence and explanatory/independent variables for injuries. (the supplementary tables present the results of the cross tabulations). However, independent of the chi square test being statistically significant or not, all the explanatory variables were tested for multicollinearity. The data were further analysed using standard logistic regression using the forward (wald) selection method based on Wald statistics to select the best minimal model. All analyses were performed using SPSS version 23.0.

3.2.4. Ethical considerations

Ethical approval was obtained from the University of Ibadan/University College Hospital Ethical Review Board. Verbal and written consent was obtained at the start of the interview, after explaining to the e-waste workers their full rights to refuse and to withdraw at any time during the interview. To ensure that the participant remains anonymous each questionnaire was coded with number identifiers. They were also assured that the data will not be used for other purposes then science and the development of safety promotion programs for the sector.

3.3. Results

3.3.1. Socio-demographic and Occupational Characteristics of the Respondents

A total of 279 (99% males and 1% females) e-waste workers were interviewed, comprising of 55% of repairers and 45% of dismantlers. The mean age of the workers was 30 ± 9 years (repairers 32 ± 8, and dismantlers 29 ± 9). Years spent on the job ranged from 1 to 32 years, and most (98%) of them work six days a week. The mean number of working hours per day was 9±2 hours, which is longer than the normal 8 working hours in Nigeria. More than half (55%) of the respondents worked for themselves, 39% were employees/apprentices, and 5% worked in the family business. A majority (89%) of the respondents worked full-time. Regarding their educational status, about 68% had secondary, 16% had post-secondary, 11% had only primary, and 4% had no formal education. However, 81% of the workers had some training on e-waste handling before starting the work, although most (98%) of the training was on-the-job training. Table 1 presents more information on the socio-demographic characteristics of the participants.

3.3.2. Use of Personal Protective Equipment (PPE)

About 35% of participants in Aba, 17% in Ibadan, and 7% in Lagos used PPE. Only 18% used PPE always, or most-of-the-time or occasionally. Among those that used PPE, only 6% used PPE always. About 82% of the workers do not use any PPE. Reasons for not using PPE ranged from “it is not important/I do not need PPE” (57%) “uncomfortable” (12%), “expensive” (11.7%), “not available” (11.4%) and “no particular reason” (7.6%). Among those that used PPE, 13% used gloves, 7% used

nose masks, 8% used boots. None of the participant used ear plugs, safety goggles, and coverall/protective wears. Figure 3.3 contains information on use of PPE among the workers and reasons for not using PPE.

Table 3.1: Socio-Demographic Characteristics of all the E-waste Workers

Demographic Characteristics		Job Designation		
		Repairers=153(54.8) n (%)	Dismantlers=126(45.2) n (%)	Total=279(100) N (%)
Location	Lagos	67 (43.8)	44 (34.9)	111 (40)
	Ibadan	48 (31.4)	42 (33.3)	90 (32)
	Aba	38 (24.8)	40 (31.7)	78 (28)
Age	30 years or less	79 (51.6)	81 (64.3)	160 (57.3)
	More than 30 years	74 (48.4)	45 (35.7)	119 (42.7)
Education	No formal Education	0(0)	12 (9.5)	12 (4.3)
	Primary	8 (5.2)	23 (18.3)	31 (11.1)
	Secondary	105 (68.6)	85 (67.5)	190 (68.1)
	Post-secondary	40 (26.1)	6 (4.8)	46 (16.5)
Training	Yes	125 (81.7)	101 (80.2)	226 (81)
	No	28 (18.3)	25 (19.8)	53 (19)
Type of training received	On-the-job training	148 (96.7)	126 (100)	274 (98.2)
	Training by an expert	5 (3.3)	0 (0)	5 (1.8)
Kind of employment	Permanent	136 (88.9)	112 (88.9)	248 (88.9)
	Temporary	17 (11.1)	14 (11.1)	31 (11.1)
Position in business	Business owner	98 (64.1)	56 (44.4)	154 (55.2)
	Employee/Apprentice	50 (32.7)	60 (47.6)	110 (39.4)
	Family business	5 (3.3)	10 (7.9)	15 (5.5)
Years of work experience	1-10 years	115 (75.2)	101 (80.2)	216 (77)
	More than 10 years	38 (24.8)	25 (19.8)	63 (23)
Work-hours/day	8 hours or less	48 (31.4)	26 (20.6)	74 (26.5)
	More than 8 hours	105 (68.6)	100 (79.4)	205 (73.5)
Income	N2000 or less	86 (30.8)	84 (30.1)	170 (60.9)
	N2001-N5000	36 (12.9)	27 (9.7)	63 (22.6)
	More than N5000	31 (11.1)	15 (5.4)	46 (16.5)

3.3.3. Occupational Injuries

Figure 3.4 presents information on injury occurrence among the workers in the timelines studied. We found a high injury prevalence of 38% (dismantlers 25% and repairers 13%) and 68% (dismantlers 37% and repairers 31%) in the last one-two weeks and 6 months and preceding the study respectively, and 89% of the respondents (dismantlers 99% and repairer 80%) reported that they had sustained an injury at least once. The mean number of injuries sustained in one-two weeks was 1±1.5. More (56% and 81%) of the dismantlers compared with repairers (23% and 57%) had been injured in one-two weeks and six months respectively. Common types of injuries sustained were cuts (59.5%), blunt injury/contusions (16%), electric shocks (14%), burns (10%), and falls (0.5%). Injuries were mainly caused by sharp objects (77%) and hammer hits (23%) during dismantling. Also 29% of the participants complained of lower back pain, shoulder pain (14%), neck pain (10%), and chest pain (5%) in the last 12 months before the study; however, 59% reported not having any pain as a result of their jobs in the last 12 months. The majority of injuries (73%) occurred on the hand/finger, 7% on the leg/foot, 5% on the chest/cough, 4% on the neck/shoulder, and about 11% reported that they never got injury at work. The majority (90%) of the workers perceived injuries from e-waste as mild/moderate. The majority (72%) of the workers reported that most of the injuries can occur at any time, while 18% indicated injuries to occur in the afternoon, 6% at night, and 4% in the morning. Fifty percent of the participants in Aba, 39% in Lagos, and 26% in Ibadan reported getting injured in one-two weeks before the study. More of the dismantlers (56% and 81%) compared with repairers (23% and 57%) got injured in one-two weeks and six months respectively; 51% of those that used PPE got injured within one-two weeks and 88% got injured within six months preceding the study. More information on the prevalence of injury among the workers are in supplementary tables.

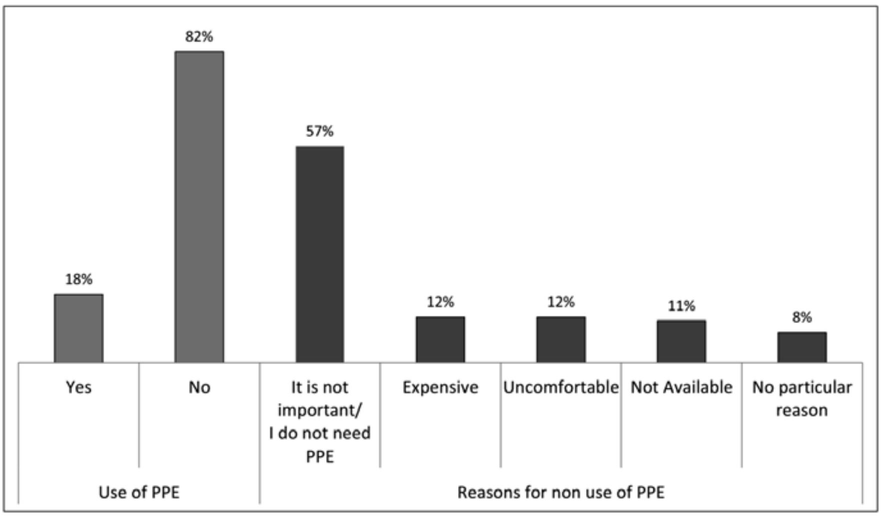

Figure 3.3 Use of PPE and Reasons for non-use of PPE

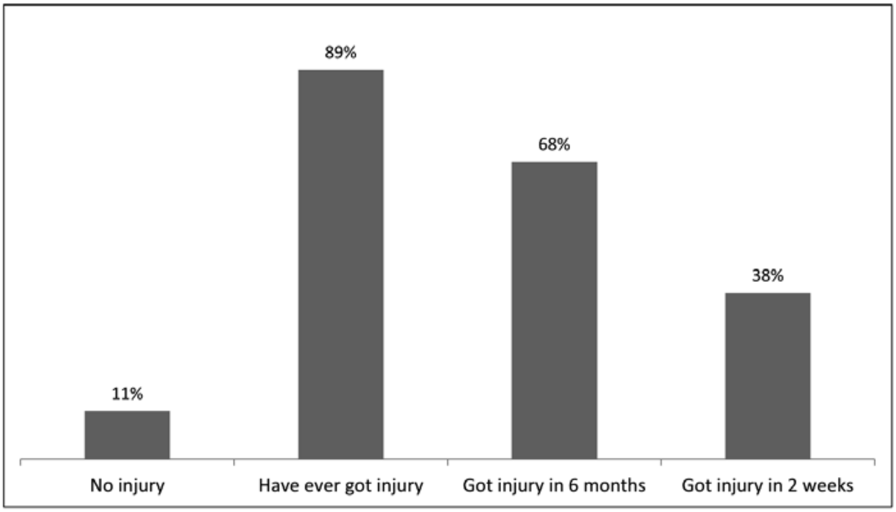

Figure 3.4 Prevalence of Injury

The multicollinearity test revealed a correlation between job designation and educational status, position in business, income, and use of PPE. There were also correlations between location and educational status; and, between years of work experience and age. Table 2 presents the odds Ratio (OR) estimates based on models of sustaining injury in one-two weeks and six months preceding the study. Bivariate logistic regression analyses indicated that job designation (type of job performed) and location were associated with sustaining injury in one-two weeks before the study. Notably, repairers are more likely to report injuries compared with dismantlers, and e-waste workers in Ibadan and Lagos are more likely to report injuries compared to those in Aba. The last two columns of table 2 present risk factors associated with injury within six months. The risk factors were job designation, location, and age, indicating likewise that repairers are more likely to report injuries than the dismantlers and e-waste workers in Lagos and in Ibadan are more likely to report injuries than those in Aba. Younger people are at higher risk of sustaining injury compared with older people.

Table 3.2: Predictors of Injury in One-to-Two Weeks and Six Months

Predictors		Injury in 1-2 weeks OR(95%CI)	P-value	Injury in 6 months OR(95%CI)	p-value
Job designation	Dismantlers				
	Repairers	4.214 (2.517 to 7.057)	0.000		
Location	Aba				
	Ibadan	3.110 (1.557 to 6.212)	0.001		
	Lagos	1.394 (0.745 to 2.610)	0.298		
Job designation	Dismantlers				
	Repairers	-		2.968 (1.652 to 5.334)	0.000
Location	Aba				
	Ibadan	-		8.071 (3.068 to 21.234)	0.000
	Lagos	-		11.773 (4.549 to 30.466)	0.000
Age	Age			1.041 (1.006 to 1.076)	0.020

3.4. Discussion

As far as we are aware, this is the first study to quantify occupational injuries among e-waste workers in the informal sector in Africa. Literature on health-related issues among e-waste workers[5,6,18] tends to provide general overviews, but provides no quantitative data which can be monitored over time to measure progress or regress in health and safety issues. The strengths of this study are its focus on the informal e-waste recycling sector which is not commonly studied, large sample size, and distribution of respondents across three major cities in two different geopolitical zones in Nigeria, quantification of injury prevalence in one-two weeks in this sector, and comparison of injury prevalence in difference timelines. However, accuracy of the data is dependent on the ability of the respondents to recall frequency of injuries.

Regarding use of PPE, the main reasons for not using PPE were “it is not important”, “discomfort”, “cost”, and “unavailability”. It is important to state that if a worker does not consider PPE as important, the worker consequently considers the costs of PPE as expensive; as a result, PPE is not available for use. A worker’s perception of the importance of the use of PPE, determines the possession, availability, and actual use of PPE. The benefits of using PPE cannot be overemphasised considering the health effects of exposure to e-waste harmful substances[5-6]. Surprisingly the use of PPE was not predicted as a factor associated with risk of injury. This finding contradicted the qualitative study by Akormedi *et al.*,[32] which state that use of PPE will reduce risk of injury among informal e-waste workers in Ghana. It also contradicted a study among miners where use of PPE was associated with risk of injury[33]. In our study, use of PPE was associated with a higher reported occurrence of injuries. This finding suggests that use PPE helps to create some awareness of potential risks of injuries among those that use PPE.

This study revealed a high injury prevalence of 38% and 68% in the last one-two weeks and six months before the study respectively, and only 18% of the workers used PPE. These findings are in line with the findings of a qualitative study in Ghana where the e-waste workers reported high frequency of injuries and no use of PPE[19,25]. Despite the high prevalence of injury among the dismantlers, the real proportion of dismantlers that got an injury in the timelines studied is expected to be higher than what they actually reported, because most of the dismantlers regarded only deep cuts with blood gushing as injuries, whereas minor and blunt injuries seem normal and are even unnoticed. The repairers are more educated than the dismantlers, they are therefore able to better and more accurately recognize and report both minor and major injuries than the dismantlers, although dismantlers do more dangerous job than repairers. This observation reveals a gross under-reporting of work-related injuries among informal recyclers as supported by Gutberlet and Baeder[26]. In addition, 29% of the participants complained of lower back pain, which is in accordance with studies that reported lower back pain as one of the most common occupational injuries[27]. The pains complained about by the participants could be a result of lack of proper physical ergonomics at work caused by working postures, repetitive movements, heavy lifting, workplace layout, and other forceful manual exertions. Despite the high prevalence of injuries, the e-waste workers do not consider injury at the work place as being problematic. This shows that common everyday risks are underrated[28].

We consider open wound injury as an additional exposure route to hazardous substances,
which implies that injuries enhances the exposure to hazardous substances. The injury prevalence in this study is higher compared with studies conducted in a similar settings among waste pickers in Nigeria within a six months period[29] and in Ethiopia within a 12-month period among small and medium scale industry workers[30,31]. This suggests that e-waste workers may be more at risk than workers in other fields of the same informal sector. The difference in injury occurrence between the two timelines is certainly not linear because the same workers may have got injured multiple times over the study period. Alternatively, we assumed that some of the injuries sustained in the six months preceding the study may not have been captured because there could be recall bias as some workers may forget some minor injuries sustained within a six months period and better remember those injuries that they sustained in a one-two weeks recall period.

Regarding use of PPE, the main reasons for not using PPE were “it is not important”, “discomfort”, “cost”, and “unavailability”. It is important to state that if a worker does not consider PPE as important, the worker consequently considers the costs of PPE as expensive; as a result, PPE is not available for use. A worker's perception of the importance of the use of PPE, determines the possession, availability, and actual use of PPE. The benefits of using PPE cannot be overemphasised considering the health effects of exposure to e-waste harmful substances[5-6]. Surprisingly the use of PPE was not predicted as a factor associated with risk of injury. This finding contradicted the qualitative study by Akormedi *et al.*,[32] which state that use of PPE will reduce risk of injury among informal e-waste workers in Ghana. It also contradicted a study among miners where use of PPE was associated with risk of injury[33]. In our study, use of PPE was associated with a higher reported occurrence of injuries. This finding suggests that use PPE helps to create some awareness of potential risks of injuries among those that use PPE.

The findings of our study suggested job designation as a risk factor for injuries among e-waste workers. This is in line with a study among Mexican workers which predicted job designation as a risk factor for injury[34]. Location as a factor may be attributed to the fact that different locations may have differing work practices. This is in accordance with the study by Gonzalez-Delgado *et al*. which found work environment and workplace conditions as risks factor for injury[34]. Furthermore, our study revealed age as a risk factor for work injuries, this was in accordance with the study by Concha-Barrientos *et al*.[28], as this study showed that younger people (≤30 years) and those who had worked for less than 10 years in the recycling business seemed to have more injuries compared with those who had worked for more than 10 years or who were older than 30 years. This could be because younger people are mostly new in the business or are apprentices/new employees, and they do the more dangerous jobs. However, Breslin *et al*.[35] stated that the reasons for higher work-related injuries among younger workers could include shorter/lack of work experience and skill, lack of use of PPE, lack of supervision, and lack of training. If these factors are taken care of, age may not be a predicting factor. About 74% of the participants worked more than 8 hours per day, which is more than the normal working hours in Nigeria[36]. However our study did not predict duration of work-years and work-hours per day as risk factors of work injuries. This contradicts the findings of Berecki-Gisolf *et al*.[37] and Dembe *et al*.[38], as these authors stated that long work hours contribute to risk of work injury.

Limitation

The accuracy of the data is dependent on the ability of the respondents to recall frequency of injuries.

3.5. Conclusions

The findings of this study are a wake-up call on the need for safety promotion programmes in the e-waste recycling sector in Nigeria. The high prevalence of injury among the e-waste workers and low use of PPE give an insight into the high risk of exposure to hazardous e-waste chemicals and the magnitude of the health problems the e-waste workers are likely to suffer in the future considering the fact that the majority of them do not use any form of PPE. There is a need for educational campaign on the health and environmental effects of informal e-waste recycling among the workers. Free PPE could be provided to the workers since the use of PPE will increase the safety awareness among the workers. Furthermore, there is a need for further research on e-waste workers' knowledge, practice, and other health outcomes they experience. Similarly, a research on the environmental risk assessment would give a deeper understanding of how many Nigerians are exposed to the harmful e-waste chemicals and to which extent they are exposed. Our study highlights the importance of occupational safety intervention in all informal sectors in Nigeria.

What is already known

- E-waste contains hazardous substances
- E-waste is recycled informally in an unsafe manner without caution to health and environment in developing countries

What this paper adds

- This is the first study that quantified occupational injuries among e-waste workers in the informal sector in Nigeria and beyond.
- The study reveals the prevalence, patterns, and factors associated with occupational injury in informal e-waste recycling sector.
- The presentation of quantitative data on work-related injuries among e-waste workers will contribute to planning for health and safety programs for e-waste workers in the informal sector, which can be extended to other informal sectors.

Policy implication

- There is need for work-place policy development to recognize the informal sector considering that the informal sector employs more than 50% of the working population in Nigeria.

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Supplementary Table 3.1a: Prevalence and Types of Injuries among all the E-waste Workers

Variables		Repairers n(%)	Dismantlers n(%)	Total N(%)
Ever got injury	Yes	123 (80.4)	125 (99.2)	248 (88.9)
	No	30 (19.6)	1 (0.8)	31 (11.1)
Got injury in 6 months	Yes	87 (56.9)	102 (81)	189 (67.7)
	No	66 (43.1)	24 (19)	90 (32.3)
Got injury in 1-2 weeks	Yes	35 (22.9)	70 (55.6)	105 (37.6)
	No	118 (77.1)	56 (44.4)	174 (62.4)
Perception of injury	Mild/moderate	146 (95.4)	106 (84.1)	252 (90.3)
	Serious	7 (4.6)	20 (15.9)	27 (9.7)
Main cause of injury	Sharps	153 (100)	62 (49.2)	215 (77)
	Hammer hits	0 (0)	64 (50.8)	64 (23)
Nature of injury	Cuts	104 (68)	61 (47.6)	164 (58.8)
	Blunt injury	0 (0)	45 (35.7)	45 (16.1)
	Electric shock	38 (24.8)	2 (1.6)	40 (14.3)
	Fire/burn	10 (6.5)	17 (13.5)	27 (9.7)
	Fall	1 (0.7)	2 (1.6)	3 (1.1)
Pains experienced with 12 months before the study	Lower back pain	41 (26.8)	41 (32.5)	82 (29.4)
	Shoulder pain	24 (15.7)	15 (11.9)	39 (14)
	Limbs(leg & hand)	21 (13.7)	15 (11.9)	36 (12.9)
	Neck Pain	15 (9.8)	14 (11.1)	29 (10.4)
	Chest pain	8 (5.2)	6 (4.8)	14 (5)
	Other parts of body	10 (6.4)	9 (7.1)	19 (6.8)

Supplementary Table 3.1b: Prevalence of Injury Among those that use PPE

		Use of PPE	
		Yes	**No**
Got injury in 1-2 weeks	Yes	26 (51)	79 (34.6)
	No	25 (49)	149 (65.4)
Injury in 6 months	Yes	45 (88.2)	144 (63.2)
	No	6 (11.8)	84 (36.8)
	Total	51 (100)	228 (100)

Supplementary Table 3.2: Factors Associated with Injury in One-Two Weeks

		Yes(injured) n(%)	No injury n(%)	Total n(%)	P-value
Job designation	Repairers	35 (33.3)	118 (67.8)	153 (54.8)	χ2=31.440,
	Dismantlers	70 (66.7)	56 (32.2)	126 (45.2)	df=1
	Total	105 (100)	174 (100)	279 (100)	p-value=0.000
Location	Ibadan	23 (21.9)	67 (38.5)	90 (32.3)	χ2=10.734,
	Lagos	43 (41)	68 (39.1)	111 (39.8)	df=1
	Aba	39 (37.1)	39 (22.4)	78 (28)	p-value=0.005
Age	30 years or less	66 (62.9)	94 (54)	160 (57.3)	χ2=2.089,df=1
	More than 30 years	39 (37.1)	80 (46)	119 (42.7)	p-value=0.148
Education	No formal Education	7 (6.7)	5 (2.9)	12 (4.3)	χ2=2.934,
	Primary	13 (12.4)	18 (10.3)	31 (11.1)	df=3
	Secondary	67 (63.8)	123 (70.7)	190 (68.1)	p-value=0.402
	Post-secondary	18 (17.1)	28 (16.1)	46 (16.5)	
Training	Yes	85 (81)	141 (81)	226 (81)	χ2=0.000, df=1
	No	20 (19)	33 (19)	53 (19)	p-value=0.986
Type of training received	On-the-job training	103 (98.1)	171 (98.3)	274 (98.2)	χ2=0.012, df=1
	Training by an expert	2 (1.9)	3 (1.7)	5 (1.8)	p-value=0.912
Kind of employment	Permanent	95 (90.5)	153 (87.9)	248 (88.9)	χ2=0.429, df=1
	Temporary	10 (9.5)	21 (12.1)	31 (11.1)	p-value=0.512
Position in business	Business owner	46 (43.8)	108 (62.1)	154 (55.2)	χ2=10.018,
	Employee/Apprentice	50 (47.6)	60 (34.5)	110 (39.4)	df=1
	Family business	9 (8.6)	6 (3.4)	15 (5.4)	p-value=0.007
Years of work experience	1-10 years	83 (79)	133 (76.4)	216 (77.4)	χ2=0.255,df=1
	More than 10 years	22 (21)	41 (23.6)	63 (22.6)	p-value=0.613
Work-hours/day	8 hours or less	24 (22.9)	50 (29.7)	74 (26.5)	χ2=1.161,df=1
	More than 8 hours	81 (77.1)	124 (71.3)	205 (73.5)	p-value=0.281
Income	₦2000 or less	72 (68.6)	98 (56.3)	170 (60.9)	χ2=8.017,df=2
	₦2001-₦5000	24 (22.9)	39 (22.4)	63 (22.6)	p-value=0.018
	More than ₦5000	9 (8.6)	37 (21.3)	46 (16.5)	
Use of PPE	Yes	26 (24.8)	25 (14.4)	51 (18.3)	χ2=4.736,df=1
	No	79 (75.2)	149 (85.6)	228 (81.7)	p-value=0.30

Supplementary Table 3.3: Factors Associated with Injury in Six Months

		Yes(injured) n(%)	No injury n(%)	Total n(%)	P-value
Job designation	Repairers	87 (46)	66 (73.3)	153 (54.8)	χ2=18.349,
	Dismantlers	102 (54)	24 (26.7)	126 (45.2)	df=1
	Total				p-value=0.000
Location	Ibadan	57 (30.2)	33 (36.7)	90(32.3)	χ2=31.858,
	Lagos	60 (31.7)	51 (56.7)	111(39.8)	df=2
	Aba	72 (38.1)	6 (6.7)	78(28)	p-value=0.000
Age	30 years or less	114 (60.4)	46 (51.1)	160 (57.3)	χ2=2.113,df=1
	More than 30 years	75 (39.7)	44 (48.9)	119 (42.7)	p-value=0.146
Education	No formal Education	9 (4.8)	3 (3.3)	12 (4.3)	χ2=17.700,
	Primary	22 (11.6)	9 (10)	31 (11.1)	df=3
	Secondary	139 (73.5)	51 (56.7)	190 (68.1)	p-value=0.001
	Post-secondary	19 (10.1)	27 (30)	46 (16.5)	
Ever received Training	Yes	159 (84.1)	67 (74.4)	226 (81)	χ2=3.715, df=1
	No	30 (15.9)	23 (25.6)	53 (19)	p-value=0.709
Type of training received	On-the-job training	186 (98.4)	88 (97.8)	274 (8.2)	χ2=0.140, df=1
	Training by an expert	3 (1.6)	2 (2.2)	5 (1.8)	p-value=0.912
Kind of employment	Permanent	166 (87.8)	82 (91.1)	248 (88.9)	χ2=0.664, df=1
	Temporary	23 (12.2)	8 (8.9)	31 (11.1)	p-value=0.415
Position in business	Business owner	89 (47.1)	65 (72.2)	154 (55.2)	χ2=15.919,
	Employee/Apprentice	89 (47.1)	21 (23.3)	110 (39.4)	df=2
	Family business	11 (5.8)	4 (4.4)	15 (5.4)	p-value=0.000
Work-years	1-10 years	146 (77.2)	70(77.8)	216 (77.4)	χ2=0.010,df=1
	More than 10 years	43 (22.8)	20(22.2)	63 (22.6)	p-value=0.921
Work-hours/day	8 hours or less	51 (27)	23 (25.6)	74 (26.5)	χ2=0.064,df=1
	More than 8 hours	138 (73)	67 (74.4)	205 (73.5)	p-value=0.801
Income	N2000 or less	132 (69.8)	38 (42.2)	170 (60.9)	χ2=22.367,df=2
	N2001-N5000	37 (19.6)	26 (28.9)	63 (22.6)	p-value=0.000
	More than N5000	20 (10.6)	26 (28.9)	46 (16.5)	
Use of PPE	Yes	45 (23.8)	6 (6.7)	51 (18.3)	χ2=11.994,df=1
	No	144 (76.2)	84 (93.3)	228 (81.7)	p-value=0.001

Chapter 4

Impact of Informal Electronic Waste Recycling on Metal Concentrations in Soils and Dusts

Based on article:
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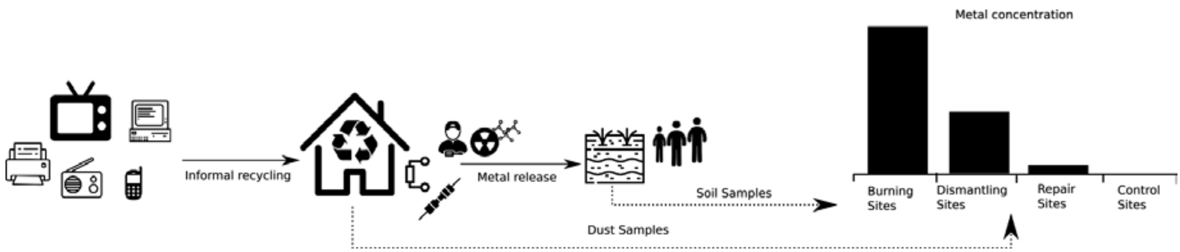

Graphical abstract

Abstract

Electronic and electrical equipment contains over 1000 different substances, including metals. During informal e-waste recycling some of these substances such as metals, are released into the environment causing environmental pollution. This study assessed the impact of different informal e-waste recycling activities (burning, dismantling, and repairing) on metal concentrations in top soils and various dust.

A comparative cross-sectional study design was adopted to assess metal concentrations in top soils and in various dust samples from multiple e-waste recycling sites. Metal concentrations at e-waste recycling sites were compared to the concentrations at control sites in three study locations in Nigeria (Lagos, Ibadan, and Aba). In the three study locations, mean metal concentrations at the e-waste recycling sites exceeded the concentrations at the control sites and the Nigerian standard guideline values by 100s to 1000s times. Burning sites showed the highest pollution level, followed by dismantling sites, then repair sites. Our findings show serious environmental and public health concerns.The metal concentrations were also higher than levels reported in other studies at the same locations in Nigeria, indicating that the situation is worsening. This study provides scientific evidence for an urgent need to develop effective strategies to strengthen enforcement of existing e-waste regulations in Nigeria.

4.1. Introduction

Information Communication Technology (ICT) has revolutionized our everyday life, consequently causing an increasing demand for ICTs. This growing importance of ICT coupled with rising obsolescence due to rapid technological advancements and decreasing electrical electronic equipment (EEE) lifetime has led to a rapid increase in the volume of waste electrical electronic equipment (e-waste) generated around the globe. E-waste refers to all items of EEE and its parts that haven been discarded by its owners as waste without the intent of re-use. It includes any product that is powered by electricity or battery (STEP Initiative 2014, Baldé *et.al* 2017), including all separate components (such as wires, cables, batteries, circuit boards) which are at the end of their useful life (Baldé *et al.,* 2015). The global estimate of *e*-waste to be generated for 2018 is 50 million metric tons (Baldé *et al.* 2015), and is expected to increase to 52.2 million metric tonnes by 2021(Baldé, *et.al* 2017). *e*-waste consists of electrical and electronic devices *e*-waste is one of the most complex waste streams because of the wide variety of components, compositions, and rapidly changing product designs. It is also one of the fastest growing municipal waste streams in the world.

There is a high level of transboundary movement of both second-hand EEE and e-waste from developed countries to developing countries. Only 20% of e-waste generated is properly collected and recycled (Baldé *et al*., 2017). About 80% of the *e*-waste generated globally is recycled in developing countries such as Nigeria, Ghana, Brazil, Mexico, China, India, Vietnam, and the Philippines in informal settings (Perkins *et al*., 2014, Awasthi *et al*., 2016). For example, in 2005, about 25%–75% of the second-hand computers imported into Nigeria were non-functional or unrepairable, and therefore were recycled informally (Ogungbuyi *et al*., 2012). Informal *e*-waste recycling processes have provided income and employment opportunities, affordable access to electronics and parts for repairs, and conservation of natural resources and energy required to manufacture new electronics from virgin resources. However, informal e-waste recycling is unsafe, unregulated, unorganised and often overlooked. Moreover, informal e-waste recycling activities release large quantities of hazardous substances (Brigden *et al*., 2008; Asante *et al*., 2012), causing environmental pollution. This is mainly due to lack of infrastructure for environmentally sound management of *e*-waste, lax environmental laws/regulations, and weak enforcement of existing laws/regulations (Terada 2012, SAICM 2009, UNEP 1991).

Electronic and electrical equipment contains over 1000 different substances, some of which are hazardous elements such as lead, mercury, cadmium, arsenic, beryllium and persistent organic pollutants (polychlorinated biphenyls and brominated flame retardants) (UNEP-DTIE) 2007). These mixtures of different substances, covering both chemicals present in EEE components and chemicals released during *e*-waste combustion, may pose significant threat on the environment (Brigden *et al*.,

2008; Asante *et al*., 2012). In addition, there may be negative consequences on human safety, given that these substances persist in the environment and have a great potential to accumulate in human and animal tissue (Akortia *et al*., 2017, Project SBCA and Pwamang 2011,Ogungbuyi *et al*., 2012, Zheng *et al*., 2013).
In the environment, soil and dust are the main receptors of emissions from informal e-waste recycling. Therefore, they are the most important environmental media that can reveal the distribution and fate of the contaminants present in the terrestrial environment (A. O. Leung, Duzgoren-Aydin, Cheung, & Wong, 2008). Moreover, dust is a good indicator for metal levels in the atmosphere (Ackah 2017, Tang *et al*., 2015, Xu *et al*., 2015, Lu *et al*., 2014, Tang *et al*., 2013, Wuana and Okieimen 2011, Banerjee 2003).

Hence, the aims of this study were to: (1) quantitatively assess the metal pollution in soil and dust because of different e-waste recycling activities (burning, dismantling, and repair sites) in three locations (Lagos, Ibadan, Aba) in Nigeria (2) determine the extent of the pollution (exceedance) at each activity site compared to the corresponding control sites. (3) evaluate factors that may influence metal concentrations at the sites (4) determine the activities that contribute most to the metal pollution to the environment. Our findings could be a wake-up call to relevant stakeholders to devise effective interventions to reduce environmental degradation caused by e-waste recycling. Our findings are likely to be applicable to other locations or countries where informal e-waste recycling is practiced.

4.2 Methods

4.2.1 Study Locations and Sites

The study was conducted in three study locations (Ibadan, Lagos, and Aba) in Nigeria. (Figure 4.1). The three study locations are some of the large cities where e-waste is recycled (Ogungbuyi *et al*., 2012). In Lagos, the selected sites were Alaba international market Ojor and Computer village, Ikeja. Alaba international market is the largest market for new and second-hand electronics in West Africa, with approximately ten to fifteen containers arriving daily from Europe and Asia (with each container containing about 400,000 second-hand units) (Osibanjo & Nnorom, 2007). Computer village Ikeja is a popular place where electronics and their parts (new and second hand) can be purchased and repaired in Lagos. In Ibadan, the selected sites were Ogunpa and Queens Cinema areas. Ogunpa area is known for its activities in scrap/second-hand businesses, which include electronics, while Queens cinema is known for sales and repair of both new and second-hand electronics. In Aba, the shopping centre and Port-Harcourt Road/Cementary and Jubilee road/St Michael's Road were selected. The shopping center area is the biggest market for new and used electronics, while the Port-Harcourt road/Cemetery area is known as an area for scrap/second-hand metal businesses in Aba.

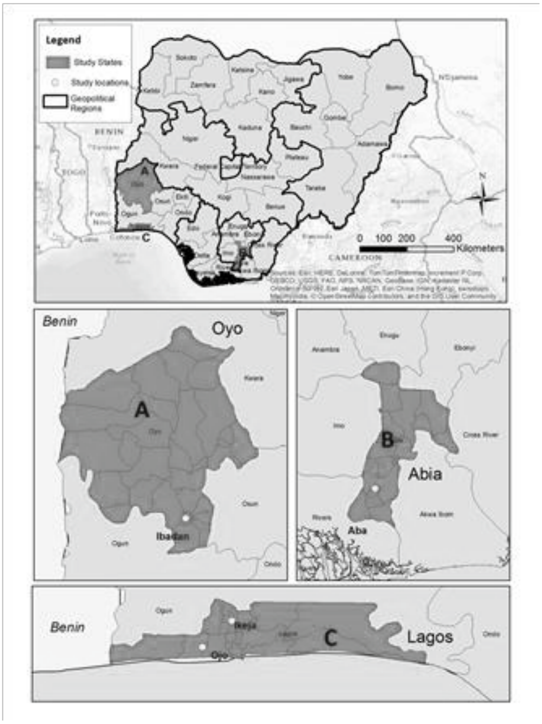

Fig. 4.1. Map of Nigeria showing the Study Locations

4.2.2 Study Design

A comparative cross-sectional study design, was adopted to gain an understanding on the metal pollution at the e-waste recycling sites compared with non-e-waste sites (control sites). In each study location, a multi-stage random systematic sampling technique was used to ensure representative inclusion of various e-waste recycling activities in the selected e-waste recycling areas. The control sites were between 100 and 500 meters away from the e-waste recycling sites, and consisted of areas with reduced human activity such as play grounds, parks, fields, and a university garden. Three types of e-waste recycling activities sites (burning sites, dismantling sites, and repair sites/shops) were analysed. In Alaba, Lagos, we found only one big e-waste burning site, which is the largest, oldest, and most studied e-waste burning and dismantling site in Nigeria. In Ogunpa, Ibadan and Cemetery area Aba, the burning sites/spots were much smaller but more spread out in small clusters around the areas. Soil and dust samples were collected from the selected sampling sites wherever possible, mostly from the burning and dismantling/scavenging sites. Dust samples were collected as ''floor dust'' from

repairer/refurbishers workshops and control sites. We also collected direct dust from the electronics. The locations of the sampling spots were georeferenced using a global positioning system (GPS) application on a phone. Constraints including the absence of unpaved surfaces or otherwise representative conditions led to an unbalanced design in soil sample collection. Figure 4.2 presents a schematic diagram of the sample collection from the various e-waste sites
in the three study locations.

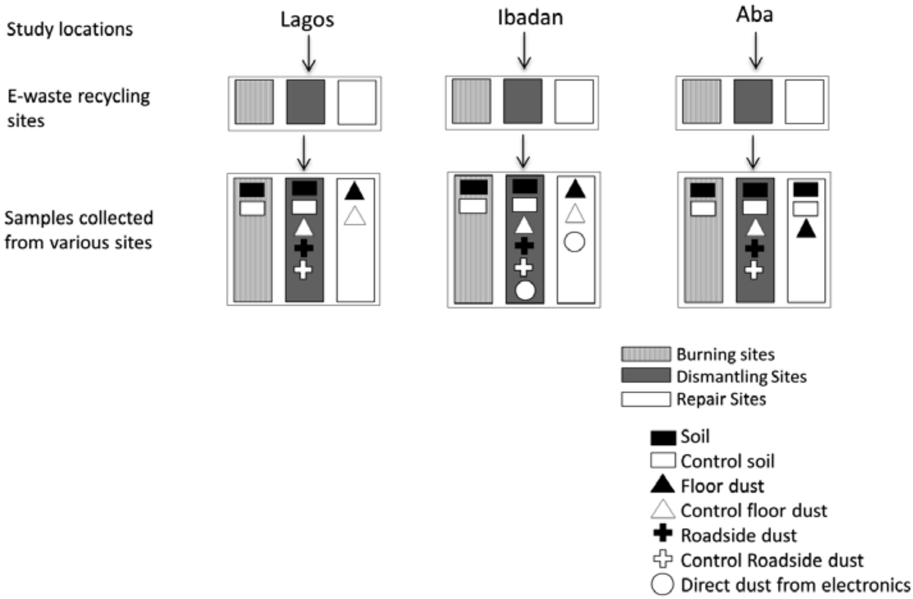

Fig. 4.2. Schematic Flow Diagram of Sample Collection in the Study Locations

4.2.3 Sample Collection and Preparation

For soil sampling, each site was divided into grids of about 10m radius, and samples were systematically collected from 3 to 6 points within the site. The samples were bulked together for the top soil (0-10 cm depth) to form a composite representative sample for the specific site. Soil samples were collected using a soil auger, and a soil trowel was used in the transfer of soil from the auger into sample wraps. To avoid cross contamination, the soil probe/auger and trowel were decontaminated (cleaned first with a brush and wiped thoroughly with wet wipes) before each sample collection at each sampling site. Dust samples were collected using plastic brushes to gently sweep the dust and collect it with a dustpan. The soil and dust samples were wrapped in an acetone treated aluminum foil, labelled, and transported to the laboratory. Soil and dust samples were air dried for 7 days, homogenized (ground with a mortar and pestle), and sieved through a 1 mm mesh sieve to remove bigger particles, transferred into treated aluminum foil and then into a zip-lock bag, and stored at -20 C. The samples were collected between May and November 2015. A total of 82 samples (62 samples from the e-waste recycling sites and 20 samples from control sites) were analysed. The samples consisted of 29 top soil (0-10 cm depth), 32 floor dust, 16 roadside dust, and 5 direct dust samples from electronics.

4.2.4 Soil Analysis

Soil pH was measured using a calibrated pH meter (691, Metrohm AG) in a (weight: volume) ratio of 1:10 of soil and tap water, adopting the USEPA method 9054D (USEPA, 2004). The soil organic matter content (TOC) was determined as the weight loss of dried soil (3hours at 100 ℃) at 550 ℃ for 5 hours(Pansu & Gautheyrou, 2006). The total metal content in soil samples was analyzed for trace elements using an X-ray fluorescence (XRF) spectrometer. For the trace metal analyses, about 3g of dry soil was introduced into a sample plastic cup with a 4-μm thick polypropylene film window, with the soil/dust samples settling on the film window. The samples were placed into the XRF spectrometer and analyzed for a fixed period of about 120 s. To check the accuracy of the analysis, each sample was analyzed at least twice. Acid-purified sand (quartz, SiO2) was used as the media blank for determining detection limits of major and trace elements and heavy metals.

4.2.5 Data Analyses

In this paper, we considered twenty-two metals Ag, As, Ba, Cd,Cr, Co, Cu, Fe, Ga, Ge, Hg, Mn,Ni, Pb, Se, Sn, Sb, Te, Ti, Ta, V, and Zn. Concentrations below the limit of detection (LOD) were set to half of the LOD (Hornung and Reed 1990). We used pollution assessment indices to evaluate and compare the pollution or contamination status/intensity of the different sites. For this study, the pollution indices employed were: the contamination factor (CF) which is a single index used to calculate contamination of each metal, and the pollution load index (PLI), which is an integrated index.

The contamination factor is the ratio of the metal concentrations of the e-waste sites to those of the ambient background concentration. We used the values obtained from the control sites as ambient background concentration because there is no data available for the natural background concentration of heavy metals in pristine soils in Nigeria. For the dust samples we used the values of the soil samples from the control sites in each location. A $CF < 1$ indicates low contamination, $1 < CF < 3$ moderate contamination, $3 < CF < 6$ considerable contamination and $CF > 6$ indicates a very high contamination level (Lars Hakanson 1980, Islam *et al*., 2015). We compared our results with the Nigerian target Soil Standard Guideline Values (SGVs) (DPR 2002). We also compared our results to one of the most used intenational SGVs - the Dutch SGVs (VROM 2000) to estimate the human health risks arising from long-term and on-site exposure to the metal concentrations that are assumed to pose a negligible risk.

The Pollution Load Index (PLI) was calculated from CF as the product of all CFs to the power of 1/n, in which n indicates the number of metals included. In this study we selected five metals of the highest concentrations (Ni, Cu, As, Sb, and Pb) to calculate the PLI (as recommended by Tomlinson *et al*., 1980). Inclusion of all the metals (including those not elevated) would have resulted in reduced PLI values, and would therefore make the PLI less suited for comparison across studies. A PLI greater than one (PLI>1) indicates progressive deterioration of the site. PLI provides an indication of the overall metal pollution of a particular site (Tomlinson, Wilson, Harris, & Jeffrey, 1980). The PLI gives the public and policy makers some understanding of the pollution level of an area/site.

Additionally, all concentrations were log transformed to bring the data distribution closer to normality. The results were summarized using descriptive statistics (frequencies, means). To understand variabilities in the distribution of metals in the environmental samples, we evaluated the differences in the metal concentrations between sites and sample types by running a series of ANOVA and t-tests on subsets of the data. This allowed dealing with the unbalanced design in sample collection shown in figure 4.2. First, a separate two-way ANOVA was run for each metal in top soil with the activity sites (burning, dismantling, and control sites) and locations as explanatory variables. Secondly, a two-way ANOVA was run for each metal in floor dust with activity sites (dismantling and repair sites) and locations as explanatory variables. Regarding the roadside dust, a series of t-tests were run (on the metal concentrations) comparing roadside dust from dismantling sites to roadside dust from control sites in Lagos, floor dust to roadside dust in Aba, and direct dust to floor dust in Ibadan. In addition, a series of two-way ANOVAs were run for location, with the activity sites (burning, dismantling, repair, and control sites) and type of samples as explanatory variables for Lagos and Aba separately. A series of two-way ANOVAs were used to test metal concentrations in various samples (soil and dust) from dismantling sites across the locations. Bonferroni posthoc tests were included to interpret the significant main effects of the ANOVA outputs. A p-value of 0.05 was considered significant. All statistical analyses were performed on log transformed data using SPSS version 23.

4.3. Results

4.3.1 Physicochemical Characteristics of the Soil

The bioavailability and mobility of metals are controlled by adsorption and desorption characteristics in soils, which are associated with pH, total organic matter content (TOC), and cation exchange capacity (CEC). The physicochemical properties of the soil samples from the study sites are presented in supplementary table S4.1. The pH for top soils ranged from 1.9 to 9.0, floor dusts 7.6 to 9.7, roadside dust sites 7.1 to 9.0, and direct dust from electronics 7.2 to 9.2. There was no significant difference between the pH of soils and roadside dusts at e-waste sites and the pH of soil and roadside dust at control sites respectively. TOC for top soils varied from 1.5 to 36.3%, floor dust 1.1 to 22.3%, roadside dust 0.5 to 6.24%, and direct dust from electronics 4.2 to 22.4. There was a significant difference between the TOC of soils and roadside dust at e-waste sites and the TOC of soil and roadside dust at control sites respectively. The soil pH controls the solubility and hydrolysis of metal. Low pH increases metal mobility/leachability thus polluting underground and surface water. Low pH also increases the bioavailability of metals to organisms, plants and the workers, therefore presenting a bigger risk than the soils with higher pH. High TOC indicates low leachability of the metals in the soil. The soil texture in Lagos and Aba is sandy loam and in Ibadan sandy clay (Nkwunonwo & Okeke, 2013).

4.3.2 Descriptive Statistics of the Metals

Supplementary tables S4.2-S4.4 present a summary of the mean and standard deviations of the metal concentrations, CF, and PLI of soil and dust samples at the various e-waste recycling sites in each of the three study locations. Widely varying standard deviations were observed for most of the elements, reflecting sample heterogeneity. The general pattern of metal distribution in top soil and dust samples from the sites showed concentrations in this increasing order: control sites < repair sites < dismantling sites < burning sites, except for Cr, V, Co, Ga and Hg which showed higher concentrations in top soils from dismantling sites compared to burning sites. The concentrations of most of the metals in top soils at burning and dismantling sites in the three locations exceeded the concentrations at the corresponding control sites and the SGVs. Overall, the metal concentrations at e-waste sites exceeded the concentrations at the control sites and the Nigerian SGVs. The pollution load index (PLI) suggested that the overall toxicity status of burning sites was highest in Lagos, followed by Aba, then Ibadan (Lagos > Aba > Ibadan), while the PLI of top soils at dismantling sites was ranked as Aba > Lagos > Ibadan. The PLI of floor dust from dismantling sites was higher in Aba than in Lagos, and the PLI for repair sites was also ranked as Aba > Lagos > Ibadan (see figure 4.3). The PLI for direct dust from electronics showed dismantling sites > repair sites (see figure 4.3). These patterns show that metal concentrations are related to the activities at the sites.

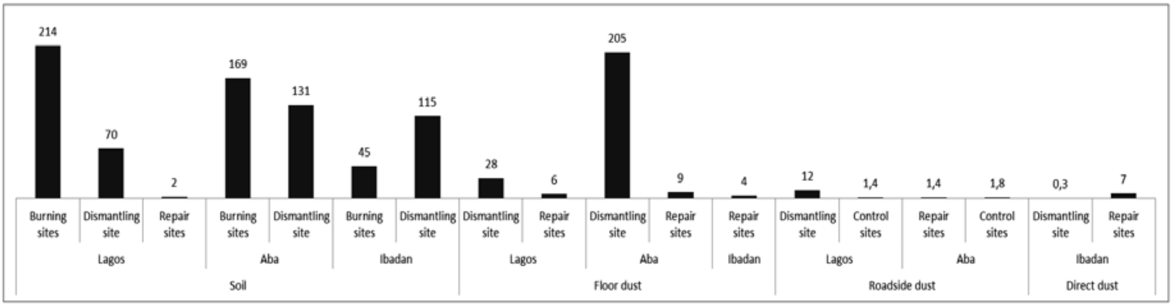

Fig. 4.3. Pollution Load Index of Soil and Dust from E-waste Recycling Sites

4. 3.3. Factors that influence the Metal Concentrations in the Environmental Media

4.3.3.1. Assessment of the top Soil Samples

Generally, the metal levels at the sites were in this order: burning, dismantling, repair and control sites, see figure 4.4. There was a main effect (influence) of activity sites on the metal concentrations (As, Ba, Cu, Ni, Se, Sn, Ta, Pb, Zn, Sb) in top soils. Besides, there was no main effect (influence) of location on the metals concentrations (except for Pb), and no interaction effect (combined influence) of location and activity sites on the metal concentrations in top soils (except for Cd). Generally, the metal concentration decreased in this order: burning > dismantling > repair > control sites. Consistently the burning sites had higher metal levels than the other sites, see figure 4.4. Supplementary table S5.5 and supplementary figure S4.1 present in detail the metals concentrations in top soil that differed significantly across the activity sites.

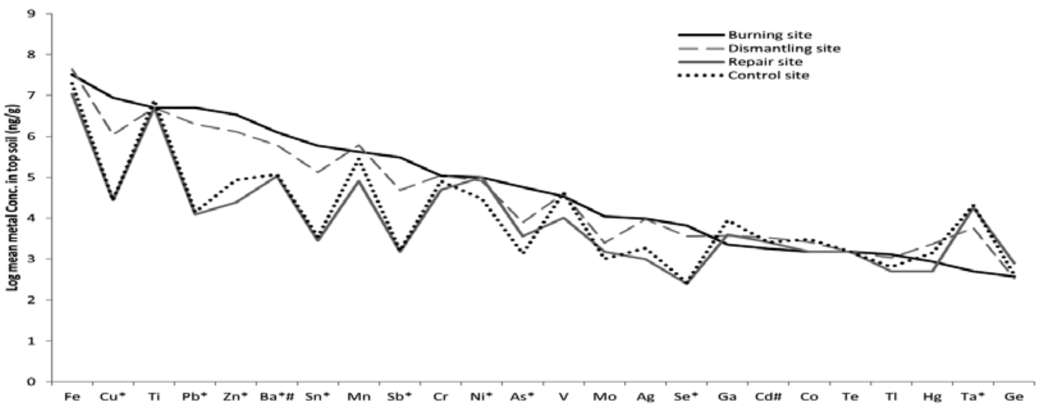

Fig. 4.4. Metal concentration in decreasing order in top soils across the sites. The metals influenced by activity at the sites are indicated with*, and interaction of activity and location with #.

4.3.3.2 Assessment of theFfloor Dust Samples

Similarly, the metal distribution in floor dust is influenced by the activities on the sites. For most metals, dismantling sites had significantly ($p<0.05$) higher metal levels than repair and control sites. Generally, the metal concentration decreased in this order: dismantling > repair > control sites (figure 4.5). Contrary to top soils, there was an interaction between location and activity sites for some metals (Fe, Cr, As, Cd, Mo) ($p<0.05$), indicating that the concentration of these metals in floor dust depend on interaction between location and activities on the sites. Supplementary table S4.6 and supplementary figures S4.2a and S4.2b provide more details on the main effects of activity sites, location, and the interaction between location and activity sites on the metals in floor dust.

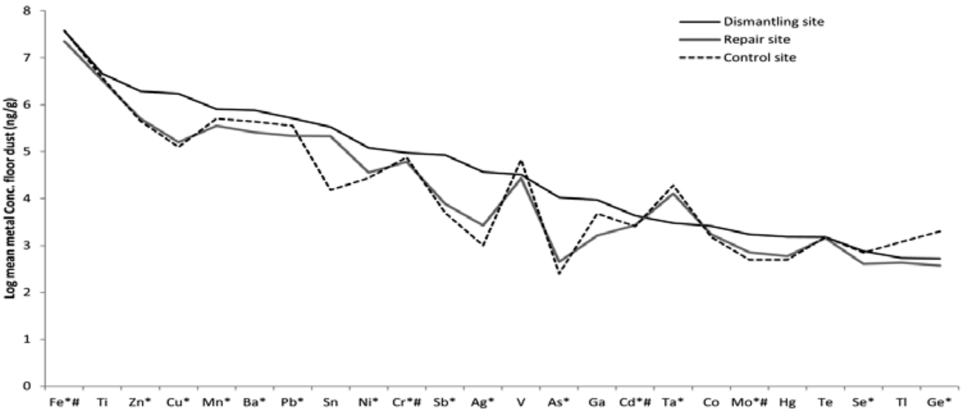

Fig. 4.5. Metal concentrations in floor dust across the sites. The metals influenced by activity are indicated with*, and interaction of activity and location with #.

4.3.3.3 Assessment of the Roadside Dust Samples

The analyses of roadside dust further confirmed that e-waste activities influence the metal concentrations, with generally, the more intense activities having higher metal concentration (dismantling > repair> control) sites, (figure 4.6). Consistently the dismantling sites had higher metal levels than the other sites. There was a significant difference in metal concentration (As, Ba, Cu, Ge, Pb, Se, and Zn) between roadside dust from dismantling and control sites in Lagos. In Aba, although the metal concentrations at the repair sites were higher than those at the control sites, the t-tests showed no significant difference between roadside dust from repair sites and control sites except for Hg which was higher at repair sites. However, there were significant differences in metal concentrations (Ni, Cu, Sb, Pb, Ga, Ge, Sn, Ti, Zn) between roadside dust from control sites and floor dust from the repair sites in Aba, with Ti, Ga, and Ge having high concentrations in roadside dust from the control sites (see supplementary table S4.7).

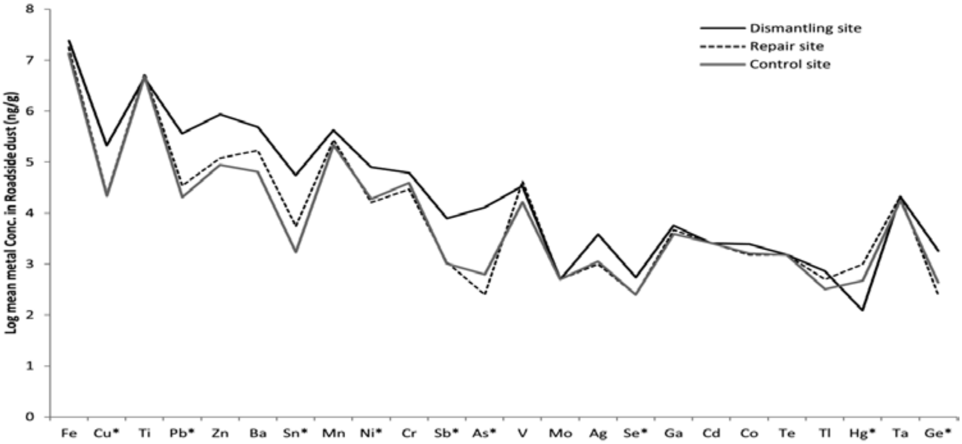

Fig. 4.6. Metal concentrations in roadside dust across the activity sites. Metal concentrations with significant difference are indicated with *.

4.3.3.4 Assessment of Direct Dust from Electronic Devices

The direct dust samples from electronic devices at the repair shops/sites had higher metal concentrations than the concentration in direct dust samples at the dismantling sites (figure 4.7). The direct dust samples from electronic devices at dismantling sites were mainly from air conditioners while at repair sites direct dust samples were collected from computers, printers and televisions. When comparing direct dust samples from electronic devices at repair sites to the floor dust samples from repair sites, a t-test showed a significant difference in the concentrations of V, Ni, Ga, As, Ti, and Ta, with the concentrations in direct dust higher than those of floor dust (see supplementary table S4.7).

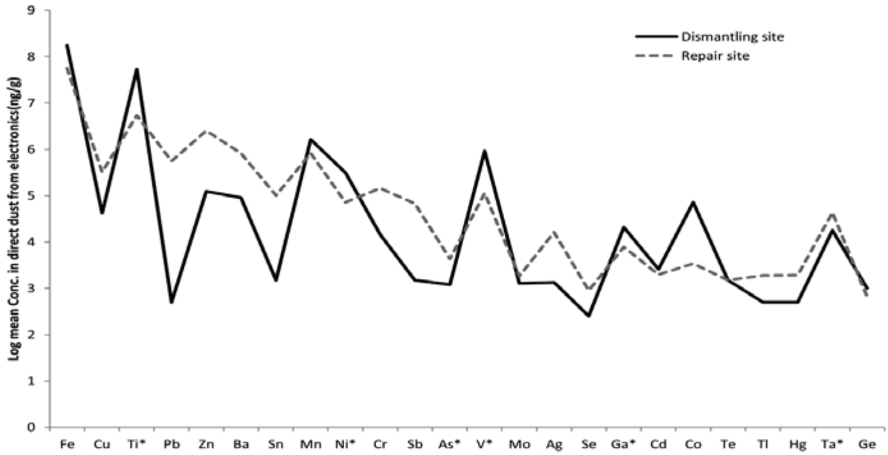

Fig. 4.7. Metal concentrations in direct dust from electronics. Metal concentrations with significant difference are indicated with*.

4.3.3.5 Assessment of Metal Concentrations in various samples from Dismantling Sites

We also evaluated the effects of location and type of sample on metal concentration at dismantling sites. A two-way ANOVA showed no interaction between type of sample and location for any of the metals, whereas there was a main effect (significant difference)of sample type on the concentrations of V, Cr, Pb, Sn, and Ti, as well as a main effect of location on the concentrations of Cd, Se,and Pb (with soils and floor dust generally having higher concentrations), see supplementary table S4.8.

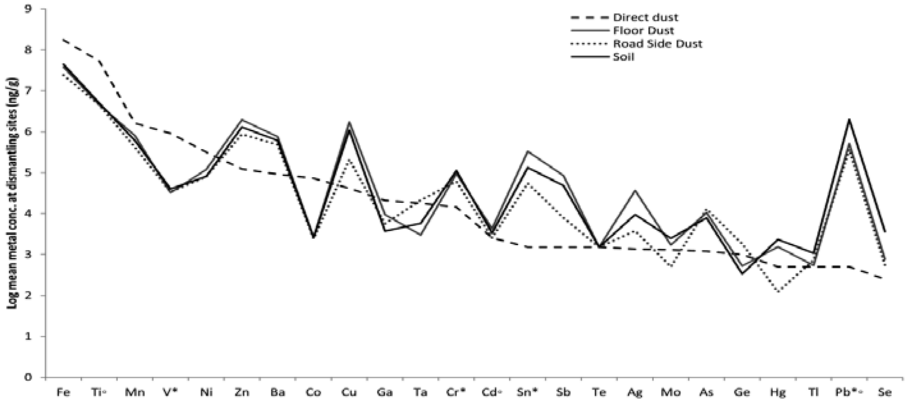

Fig. 4.8. Metal concentrations in various samples. Metal concentrations with significant difference are between the locations (indicated withº) and activities (indicated with*)

4.3.3.6 Assessment of Metal Concentrations from different e-waste sites in the same Location

With a series of a two-way ANOVA, we compared the various metal concentrations in soil vs. dust samples from the activity sites within Lagos and Aba. Whereas there was no main effect of type of sample and no interaction effects between type of sample and activity sites for any metals, again, there was main effect of activity sites on the concentration of almost all the metals in the two locations (see supplementary tables S4.9 and S4.10 for Lagos and Aba, respectively).

4.4 Discussion

Most *e*-waste recycling activities (especially at dismantling and burning sites) are carried out outdoors. The recycling activities include storage, washing, cleaning, dismantling, and metal recovery through stripping of wires or open burning. Open burning leads to incomplete combustion and processed materials from the various e-waste activities are dumped outside on bare ground. Most repair activities, which involve soldering of various parts, take place indoors but also sometimes outdoors, depending on the work environment. These activities release large quantities of hazardous substances without any emission control. Soils and dusts are a major repository for pollutants released into the environment by human activities, and they are significant environmental media that can provide information about the level, distribution, and fate of contaminants present in the environment as a result of informal e-waste recycling (SCU, 2013).

As far as we are aware, this is one of the few studies that conducted analyses of the metal concentrations in soil and dust samples from different e-waste activity sites (burning, dismantling, and repair sites) as compared to control sites in three different cities. The strengths of this study are its focus on different e-waste sites in each city, analyses of more number of metals that are not usually reported in other studies, the comparison of metal concentrations in various environmental samples (top soils, floor dusts, roadside dust, and direct dust from electronics) from different e-waste recycling sites and corresponding control sites, and the comparison of the extent of metal pollution at e-waste sites across the three cities in two different geopolitical zones in Nigeria. So far most studies (Isimekhai *et a*l., 2017, Adesokan and Gilbert 2016, Adeyi 2017, Adaramodu *et al*., 2012) on metal pollution due to informal e-waste recycling sites focused on one location and usually on one type of environmental sample only. Therefore, these did not provide a comprehensive view on the extent to which heavy metal pollution from these activities is a problem.

Despite the increasing volumes of e-waste generated over the years, collection and recycling of e-waste are still not improved in developing countries (Ackah, 2017). Nigeria imports the largest volume of new and used electronic and electrical equipment in Africa (Ogungbuyi *et al.*, 2012). The amount of e-waste generated in Nigeria increased from 219 kilo tonnes in 2014. (Baldé *et al.,* 2015), to 277 kilo tonnes in 2016 (Baldé *et al.,* 2017). The majority of the e-waste is recycled in an unsafe/informal manner (Ogungbuyi *et al*. 2012, Baldé *et al* 2017), releasing chemicals into the surrounding environment, which consequently has become a serious burden on the Nigerian ecosystem. This situation in Nigeria is likely to be representative for informal e-waste recycling in countries that lack the resources for safe e-waste recycling such as in China (A. O. Leung *et al.*, 2008), India, Brazil, Mexico (Lundgren, 2012), and Ghana (Akortia *et al.*, 2017) among others.

In our study we included all types of e-waste recycling activities sites-burning, dismantling, and repair), and included dust samples. The added value of determining the metal concentrations in dust samples was to ensure a representative assessment of metal pollution by various e-waste activities, considering that some activities (such as repair activities) do not take place on soil (bare ground) most of the time. Also, dust provides information about the level of contaminants in the indoor atmosphere as well as the level of contaminants to which the workers and the public are exposed. Considering that one of the main sources of exposure to metals is via dust inhalation or ingestion. Dust also reflects the characteristics of short and long term activities in the area. We expect a cross transfer of metals from the floor dust (indoor) in to the soil, and from the soil at burning and dismantling sites into the shops (contaminating floor dust).

4.4.1 Extent of Pollution as a Result of Informal e-waste Recycling

We found extremely high concentrations of toxic metal contained in electronics (Kumar *et al*., 2017 and Hageluken *et.al.* 2013) at the e-waste sites, with concentrations as high as 38530 mg/kg (Pb), 148 mg/kg (As) 13 mg/kg (Cd), 9 mg/kg (Hg) in Ibadan. In Lagos, concentrations as high as 1544 mg/kg (Sb) and 195 mg/kg (Ni), and in Aba, concentrations as high as 180 mg/kg (Cr) and 21270 mg/kg (Cu) were found. We found Pb levels in floor dusts at dismantling and repair sites in Aba exceeding the Pb levels at the controls sites by 7540 and 1058 times respectively. These metals are of public health importance, and these high levels of metals call for concern. However, some of the elements contained in electronics (Ga, Cd, Co,Hg,Ta,Ge) were not as elevated as the others and were more elevated at the dismantling or repair sites compared to the burning sites. This could be because these elements are in very small quantity in electronics, and the components of the electronics containing these elements may not be part of the electronics that undergo open burning; for example, the capacitors and the printed circuit board which are just removed as we observed. Ta was significantly higher at the repair and control sites than the burning and dismantling sites. In Aba, we also found some of the transitional metals (Ti, Ga, and Ge) to be higher in the roadside dust from control sites than the levels in floor dust for reasons not known. Overall, the metal concentrations at e-waste recycling sites exceeded by many folds the concentrations at the control (non-e-waste) sites and the Nigerian and Dutch target SGVs except for Co. Sb, Cu, Pb, As, and Ni are the most enriched metals in the top soils. This is in accordance with results found in Nigeria by Isimekhai *et al*., 2017, in Ghana by Akortia *et.al* 2017, and in China by Li *et al*., 2011 where the e-waste recycling sites had higher concentrations of the metals compared to control sites

Soil metal toxicity and bioavailablity are not only dependent on the total metal concentration in the soil, but also on other physiochemical parameters of the soil such as pH, organic matter content, soil texture. The physiochemical parameters of the soil control the availability of the metals. A very low pH of 1.94 was found only at a battery dismantling sites in Ibadan. Due to this low pH, the mobility and availability of metals from these sites to adjacent areas, and contamination of surface and underground water might be very high, which can cause harmful effects. Due to the high metal concentrations at the sites together with low pH at the battery dismantling sites, the workers are at risk of metal exposure. The e-waste sites had high metal concentrations, a mean pH of 7 ± 2.2, and a high mean TOC of 12 ± 9.4, indicating that the metals at the sites/areas have a low mobility/leachability and low availability to the ecosystem. In addition, informal e-waste recycling activities (burning and dismantling) in developing countries like Nigeria happen mostly in the urban slums with poor sanitary conditions such as poor drainage sytems among others (Ha *et al*., 2009, Awasthi *et al*., 2016b, Akortia *et al*., 2017). The continuous accumulation of metals due to the activities carried out in the burning and dismantling areas could exceed its storage capacity. This would likely cause a serious problem of contamination in the nearby locations. The soils could become a problem if e-waste recycling activities are not controlled and corrective measures applied on time. The excessive metal accumulation in these areas and continuous contact of workers with soils with high metal concentrations can be a risk to their health. Despite the low bioavailability of these metals in the soil, the workers are directly in contact with these pollutants, with possibilities of exposure via dermal contact, inhalation and mistaken ingestion.

The combined application of CF and PLI can effectively identify the single and comprehensive pollution levels of elements at the e-waste sites, which is important for assessing the extent of metal pollution in the environment. The quantitative pollution indices showed a consistent pattern. Overall, there was an increasing trend of pollution as the intensity of the e-waste activities increased. The various e-waste sites showed higher metal concentrations in accordance with the type/intensity of the e-waste activity in the increasing order of control sites < repair sites < dimantling sites < burning sites. In addition, the PLI showed soils as being most polluted floor dusts and roadside dusts (soil > floor dust > roadside dust). The pollution indices confirm that the contamination is as a result of e-waste recycling activities at the sites. The PLI of the e-waste sites showed higher metal concentrations in accordance with the type/intensity of the e-waste activity, in the increasing order of control sites < repair sites < dimantling sites < burning sites. This finding reveals that open burning of e-waste is the most polluting e-waste processing/recycling activity. This is in agreement with other studies where the focus was only on soil samples for e.g in Nigeria by Isimekhai *et al*., (2017), in Ghana by Akortia *et al*., (2017), in China by Wong *et al*., 2007, and in India by Pradhan and Kumar (2014). In these studies too, it was concluded that burning sites had higher metal concentrations than the dismantling sites.

The analyses and the relative metal distributions in the various sample types showed that the type of activities on the sites has a major effect on metal concentrations. While e-waste recycling acitivities had strong effect on of metal pollution, location did not have any significant effect on metal concentrations in top soils except for Pb. This effect on Pb concentration was due to the effects from Ibadan where we sampled battery recycling sites. The non- significant difference in metal concentrations between locations shows that there is no external influence on the metal concentrations found at the sites. On the contrary, in floor dust there was a main effect of location and interaction effect of activity and location on some of the metal concentrations (Cr, As, Mo, Cd, Fe). This means that both activity and location influences the metal concentration in the floor dust.

The PLI showed soil as being most polluted, followed by floor dust, then roadside dust (soil > floor dust > roadside dust). An explanation to this finding could be that the floors of the workshops are swept daily. The roads are also swept, but not daily while the chemicals released on the soil during the e-waste recycling activities are deposited on the soil. In our case study, e-waste burning took place in the open on bare ground, directly on the soil. The accumulation of the metals and deposition of residues after burning and dismantling at the sites could have implications of directly polluting surface and underground water, increasing metal uptake by plants, as well as inducing accidental ingestion, especially by children. Sweeping the floor of the workshops might explain why the metal levels in the soils were higher than the levels in the dust samples. Therefore the soil could be reflecting the real long-term impact of the e-waste dismantling activity on the environment. However, the floor dust from the dismantling workshops used as storage that are not swept daily had a higher PLI value than soils from dismantling sites, see supplementary table S4.4.

Metal concentrations in roadside soils/dusts reflect the pollution levels from anthropogenic sources in urban areas. Overall, the pollution load indices (PLI) of floor dusts and roadside soils/dusts from all the sites were greater than one (PLI > 1), which indicates that the area/site is polluted. This is an indication that the toxic elements in the electronics contaminate the urban environment. In Aba, the Pb concentrations in roadside dust from repair and control sites were higher than the Pb concentrations in roadside dusts in 2007 and 2008 as reported by Nduka and Orisakwe (2010). In addition, the metal concentrations (Pb, Cd, Cr) in roadside dusts from the control sites in Lagos were higher than the levels found in 2012 by Adaramodu *et al.*, in 2012. These findings further show that the metal pollution of the environment in urban cities in Nigeria is increasing. It is also noteworthy that the value of the PLI for direct dust samples from the electronics at repair sites was higher than the PLI value for floor dusts from repair sites in the same location (Ibadan). This is an indication of contamination in the indoor environment.

4.4.2 Implications of High Metals Concentrations in the Environment

No doubt, e-waste recycling is major source of metal pollution in Nigeria. Metals are naturally occurring elements, but anthropogenic sources (such as e-waste) of metals can alter the distribution of the metals in the environment. There is a tendency for elements introduced with solid waste to be less strongly bound than those in natural compounds. Therefore, metals from anthropogenic sources are relatively easily mobilized. Transportation of the metals to ground water, surface water, sediments, soils, aquatic organisms, air, plants is a considerable environmental concern. These metals subsequently enter the food chain, and successive accumulation and bio-magnification in human tissues threatens human health. The potential health effects are anemia, fatigue, gastrointestinal problems and anoxia, difficulties in pregnancy, high blood pressure, muscle pain, joint pain, permanent brain damage, and the popular the Itai-itai disease in Japan caused by Cd pollution (Nriagu 1981, Lalor 2008). Metals of public health significance, which can induce multiple organ damage even at extremely low concentrations (Tchounwou, Yedjou, Patlolla, & Sutton, 2014) such as As, Cd, Cr, Pb, Ni, and Hg were found in high concentrations at the sites. Heavy metal pollution adversely affects soil biota by affecting key microbial processes, resulting in the change of diversity, composition, population, and overall activity of the soil microbial communities (Wang *et al*., 2007,Singh and Kalamdhad 2011). Metal pollution can cause phytotoxicity resulting in chlorosis, weak plant growth, reduced nutrient uptake, reduce nitrogen fixation in legume plants, disorders in plants metabolism(Guala *et al*., 2010). In addition, heavy metals are non-biodegradable, highly persistent in the environment, and can disturb the ecological balance of the aquatic environment, thus affecting the diversity of the aquatic organisms depending on the extent of the pollution(Ayandiran *et al*., 2009). Metals released into the environment can also settle into the sediment, which would be eventually taken up by aquatic macrophytes and other aquatic organisms (Peng *et al.*, 2007), including fish hence affecting the aquatic organisms adversely. Metals can also dissolve in water, are easily absorbed by aquatic organisms, and decreases the water quality posing a health risk to humans.

Comparing the metal levels to those reported in previous studies in the same areas, it is found that metal concentrations are increasing (Olafisoye et al. 2013, Isimekhai et al. 2017,Adesokan and Gilbert 2016, Adeyi 2017). The metal concentration at the burning sites were also higher that the concentration reported in studies in China (Yekeen et al. 2016, Awasthi et al. 2016). This is more disturbing as majority of the e-waste workers are unaware of the health risks associated with their jobs (Ohajinwa et al. 2017). Our results show an urgent need for action to stop open burning of e-waste and to reverse/stop the environmental deterioritation as a result of informal e-waste recycling. Nigeria is a representative of e-waste recycling in developing countries, and a solution profferred for Nigeria can be applied in other countries.

4.5. Conclusions

It is evident that informal e-waste recycling pollutes the environment, with the burning activities having the most impact, followed by dismantling, then repair activities. Metal concentrations at the e-waste recycling sites exceeds the concentrations at control sites by 100s to 1000s times on most of the metals. Our findings provide a evidence for an urgent need to develop effective strategies to strengthen enforcement of existing interantional and national e-waste regulations to curb the environmental and health risks posed by informal e-waste recycling presently and the unforseen furture. Comparing our results with past studies in the same locations, the metal concentrations are increasing, suggesting that the situation calls for urgent action.

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Supplementary Table S4.1: Physicochemical Parameters (pH and Organic Matter Content) of the Soil samples within the Study Site

E-waste activity sites		Lagos				Ibadan				Aba			
		pH	Control pH	%TOC	Control %TOC	pH	Control pH	%TOC	Control %TOC	pH	Control pH	%TOC	Control %TOC
Burning sites													
Soil(0-10cm)	Mean ± SD	7.7	7.9±0.4	36.3	3±0.5	8.2±0.2	8.2±0.24	16.8±2.4	3.6±1.6	7.6±0.34	7.5±0.62	14.54±8.6	2.3±0.7
	Minimum	7.7	7.41	36.3	2.4	8.03	8.1	15.1	2.5	7.21	7.10	7.98	1.8
	Maximum	7.7	8.22	36.3	3.4	8.4	8.4	18.45	4.7	7.84	7.97	24.24	2.8
Dismantling site													
Soil(0-10cm)	Mean ± SD	7.94±0.9	7.9±0.35	9.5±9.8	3.5±1.2	6.1±2.91	8.2±0.24	9.4±7.67		8.28	7.5±0.62	17.85	2.3±0.7
	Minimum	7.74	7.41	1.58	2.46	1.94	8.07	2.74		8.28	7.10	17.85	1.8
	Maximum	8.2	8.22	23.69	5.15	9.0	8.41	29.24		8.28	7.97	17.85	2.8
Floor dust	Mean ± SD	8.4±0.24		4.9±1						7.8		11	
	Minimum	8.14		3.71						7.8		11	
	Maximum	8.7		6.19						7.8		11	
Direct dust from electronic	Mean ± SD					7.2		4.2					
	Minimum					7.2		4.2					
	Maximum					7.2		4.2					
Roadside dust	Mean ± SD	8.3±0.6	8.2±0.6	4.4±2.6	1.3±0.4					8.06	8.15±0.6	1.51	1.3±0.35
	Minimum	8.25	7.6	2.61	0.98					8.06	7.1	1.51	0.6
	Maximum	8.34	8.7	6.24	1.6					8.06	9.0	1.51	1.7
Repair site													
Floor dust	Mean ± SD	8.5±0.5		3.4±0.95		8.5±0.5		9.1±7.6		8.2±0.25		2.6±0.92	
	Minimum	8		1.85		7.64		3.4		7.95		1.14	
	Maximum	10		5.01		8.96		22.33		8.8		3.86	
Direct dust from electronic	Mean ± SD					9 ± 0.2		17.4 ± 5.6					
	Minimum					8.8		9.9					
	Maximum					9.2		22.4					

Supplementary Table S4.1b: Physicochemical Parameters (pH and Organic Matter Content) of the Samples at the Study Site

Samples	E-waste sites		Control sites	
	pH	**TOC%**	**pH**	**TOC%**
Soil	7± 2.2	12±9.4	8± 0.4	3.2±1.2
Roadside dust	8.2±0.6	1.2±0.4	8.2±0.14	3.5±2.5
Floor dust	8.4±0.4	5±4.4	8.8±0	5.3±0
Direct dust	8.6±0.8	14.7±7.6	-	-

Supplementary Table S4.2: Mean Metal Concentrations (mg/kg), Contamination Factor (Exceedance), and Pollution Load Index of Soil and Dusts across various E-waste Sites in Ibadan

	Top Soil					Floor dust			Direct Dust					
Metal	**BS** (mg/kg)	**DS** (mg/kg)	**CS** (mg/kg)	**CF**	**CF**	RS (mg/kg)	CS (mg/kg)	**CF**	DS (mg/kg)	**CF**	RS (mg/kg)	**CF**	NSGV	DSGV
				BS	DS			RS	DS		RS			
V	54±3.2	52±24	80±12	0.7	0.7	68 ±21	67	0.8	922±0	11.5	118±44	1.5	42	
Cr	123±43.8	117±55	141.1±55	0.9	0.8	118± 20	75.5	0.8	14±0	0.1	150±50	1.1	100	42
Co	1.5 ±0	15.5± 44	8.3±1.4	0.2	1.9	3 ±3	1.5	0.3	72±0	8.7	11±19	1.3	20	100
Ni	93±56.4	95± 62	51.3±18	1.8	1.9	51±16	28	1	320±0	6.2	77±30	1.5	35	9
Cu	12749±3976	3399±4893	70±27	183	48.7	428± 351	126	6.13	42±0	0.6	595±724	8.5	36	35
Zn	3327±901	2724±3035	300±17	11	9.1	1245±512	446	4.15	122±0	0.4	2564±674	8.6	140	36
Ga	5.2±7	9±9	9±3	0.6	1.04	3±2.4	4.8	0.35	21±0	2.5	8.5±4	1		140
Ge	0.25± 0	0.4±0.3	1±1	0.2	0.4	0.6±4	2	0.54	1.1±0	0.9	1.05±1.1	0.9		
As	103±64	22± 22	4±5	27	5.7	1.4±3	0.25	0.38	1.2±0	0.3	18±30	4.8	29	
Se	26±30	14±18	0.5±0.5	55	30	3±3	0.7	5.5	0.25±0	0.5	1.4±1.4	2.8		29
Mo	8± 0.4	6.5±7	4±3	1.9	1.55	1.7±1.5	0.5	0.4	1.3±0	0.3	2±1.4	0.5		
Ag	16±6.7	19± 28	14±19	1.1	1.4	15±28	1.0	1.1	1.4±0	0.1	19±12	1.3		3
Cd	7± 9.1	5± 6	2.55 ±0	2.8	2.02	2.8±1.6	2.55	1.1	2.6±0	1.0	3±2.7	1.2	0.8	
Sn	1214±489	202± 160	44±44	27	5	2190±3948	15	49	1.5±0	0.03	313±533	7.1		0.8
Sb	592±346	78 ± 56	2 ± 0.7	296	39	43±74	5.0	22	1.5±0	0.8	199±322	100		
Te	1.5 ± 0.0	1±0	1.5 ±0	1	0.7	1.5 ±0.0	1.5	1	1.5±0	1.0	1.5±0	1.0		
Ba	930±418.5	638±250	638±269	1.5	1.	452±136	436	0.7	90±0	0.1	1944±2502	3.1	200	
Hg	5±5.8	6±7	1.1 ±0.8	4.4	5.7	1±1	0.5	0.9	0.5±0	0.5	2.5±1.6	2.4	0.3	160
Ti	6595±24193	4994±2244	5265±744	1.25	0.95	3547±590	5032	0.8	53190±0	10	5600±1846	1.1		0.3
Pb	21423±24194	11757±16964	305±107	70	38.6	1767±2832	353.4	5.8	0.5±0	0.0	759±751.6	2.5	85	
Ta	0.5±0	30±37	21±1	0.02	1.43	15±4	19	0.7	18±0	0.9	49±31.8	2.4		85
Fe	31435±7191	62896±51698	35835±6993	0.9	1.8	50009±17461	38440	1.4	1607±0	0.04	59650±22404	1.7		
Mn	740±460	859±805	597±16	1.2	1.4	740±164	502	1.2	175000±0	293	871±367	1.5		
PLI				**45**	**15**			**4**		**0.3**		**6.9**		

CF= Contamination factor,PLI= Pollution Load Index,NSGV= Nigerian Standard Guideline Values, BS= Burning sites, DS= Dismantling sites, RS=Repair sites,CS=Control sites

Supplementary Table S4.2: Mean Metal Concentrations (mg/kg), Contamination Factor (Exceedance), and Pollution Load Index of Soil and Dusts across various E-waste Sites in Lagos

	Top Soil							Floor dust				Roadside dust		
Metal	**BS** (mg/g)	**DS** (mg/g)	**RS** (mg/kg)	**CS** (mg/g)	**CF**	**CF**	**CF**	**DS** (mg/kg)	**CF**	**RS** (mg/kg)	**CF**	**DS** (mg/kg)	**CS** (mg/kg)	**CF**
					BS	DS	RS	DS		RS				DS
V	24±0	51±46	10±0	36.5±16	0.7	1.4	0.3	36±11	0.98	25±11	0.7	35.2 ± 13	23±14	1.0
Cr	69±0	118±52	49±0	72±19	0.95	1.6	0.7	81±24	1.13	54±16	0.8	62.5 ± 21	57±8	0.9
Co	1.5±0	3.4±2.6	1.5±0	1.5 ±0	1	2.26	1.0	7±11	4.6	1.7±0.6	1.1	2.8± 1.8	2±1,2	1.8
Ni	194±0	103±116	100±0	18±0.7	10.6	5.6	5.5	131±88	7.2	50±37	2.7	83 ± 32.2	52±51	4.5
Cu	12590±0	3199±5396	28±0	18±7.8	684	174	1.5	2062±2904	112	157±203	8.5	235.8± 15	15±5.	13
Zn	3152±0	2534±3920	25±0	46.4±15	67.9	55	0.5	1616±7775	34.8	415±286	8.9	924± 462	108±91.	20
Ga	1.5±0	12.4±8.6	4±0	7.9±1.6	0.2	1.6	0.5	8.6±2.7	1.1	3.5±2.7	0.5	6±2	4±2	0.7
Ge	0.3±0	0.6±0.4	0.8±0	0.4±0.2	0.6	1.4	2.0	0.8±0.7	2.0	0.4±0.3	1.1	2±1.3	0.3±0.2	5.1
As	83±0	25±43	3.6±0	0.7±0.4	119	35	5.1	8.4±7	12	1.3±1.8	1.9	13±3	1.2±0.9	19
Se	6±0	2.4±4.4	0.3±0	0.25±0	24	9.5	1.0	0.7±0.6	2.9	0.4±0.4	1.6	0.6± 0.1	0.3±0.0	2.2
Mo	8.5±0	5.6±10.2	1.5±0	1.2±1.2	7.1	4.7	1.3	2.1±3.1	1.7	0.7±0.5	0.7	0.5±0	0.5±0	0.4
Ag	41±0	80±152	1±0	2.5±2.5	16.4	32	0.4	38.5±17	15.4	6.3±7.3	2.5	7.7± 9	0.9±0.3	3.1
Cd	10±0	2.4±0.4	2.6±0	2.6±0	4	0.9	1.0	2.6±0.2	1.04	3.5±3.1	1.4	2.6± 0	2.5±0	1.0
Sn	2722±0	876±1678	2.8±0	1.5±0	1815	584	1.9	352.7±236	235	478±748	319	63.1±43.6	2.2±2.1	42
Sb	1544±0	523±1017	1.5±0	1.3±0.3	1161	394	1.1	84.5±94	63.5	10±13.5	7.4	13.6± 17	0.9±0.6	10
Te	1.5±0	1.5±0	1.5±0	1.5± 0	1	1	1.0	1.5±0	1.0	1.4±0.3	0.9	1.5±0.0	1.5±0	1.0
Ba	1378±0	1525±2643	107±0	71±22.5	19.4	21	1.5	782±400	11	225±60	3.2	498±163.8	160.5±48	7.0
Hg	0.5±0	10.2±16.7	0.5±0	0.5±0	1	20	1.0	3.3±3.4	6.6	1.4±2.7	2.7	0.2±0.2	0.5±0	0.4
Ti	4546±0	7745±2968	5108±0	7981±1802	0.57	0.9	0.64	4546±859	0.6	3272±799	0.4	4538±210	4417±336	1.5
Pb	6358±0	1723±3149	12±0	14±3	445	121	0.9	370±264	26	265±393	18.5	373.6±118	25.2±14	26
Ta	0.5±0	19±14.4	18±0	17±2	0.03	1.1	1.1	6.7±5	0.4	15.5±5.8	0.9	21±1	19.1±4	1.2
Fe	7373±0	34140±17225	11000±0	12336±2995	0.6	2.8	0.9	30620±7749	2.5	17094±6687	1.4	24720±7029	13415±4913	1.2
Mn	160±0	672±153	81±0	124±29	1.3	5.4	0.7	1083±965	8.7	288±105	2.3	426±73	261±108	0.6
PLI					**213.8**	**69.7**	**2.1**		**27.5**		**5.7**			**12.3**

CF= Contamination factor,PLI= Pollution Load Index,NSGV= Nigerian Standard Guideline Values, BS= Burning sites, DS= Dismantling sites, RS=Repair sites,CS=Control sites

Supplementary Table S4.4: Mean Metal Concentrations (mg/kg), CF, and PLI of Soil and Dusts across various E-waste sites in Aba

	Top Soil					Floor dust				Roadside dust			NSGV	DSGV
Metals	**BS** (mg/kg)	**DS** (mg/kg)	**CS** (mg/kg)	CF	CF	DS (mg/kg)	CF	RS (mg/kg)	CF	RS (mg/kg)	CS (mg/kg)	CF		
				BS	DS							RS		
V	31± 13	46±0	39±44	0.8	1.2	26±0	0.7	18±5.9	0.5	42±0	23± 14	1.1	42	42
Cr	125 ± 47	197±0	63±15	2	3.1	188±0	3	45±10.7	0.7	29.5±0	38±15	0.5	100	100
Co	1.5± 0	1.5±0	1.5±0	1	1	1.5±0	1	1.5 ±0.0	1.	1.5±0	1.5± 0	1	20	9
Ni	90± 14	153±0	20±6	5	8	149±0	7.6	26±9.8	1.3	16±0	16±5	0.8	35	35
Cu	9420±10306	7880±0	21±3	450	376	13580±0	648	364±476	17	23±0	25± 13	1.1	36	36
Zn	4533±3553	5650±0	85±14	53	66	5401±0	63	453±244	5	119±0	103±48	1.4	140	140
Ga	8.4± 7	14.5±0	10±5	0.9	1.5	15±0	1.5	3± 3.2	0.3	4.7±0	4±2	0.5		
Ge	0.6± 0.4	0.25±0	0.5±0.3	1.3	0.5	0.3±0	0.5	0.3 ± 0.1	0.6	0.25±0	0.6±0.2	0.5		
As	48.1± 45	40±0	2.0±0.3	24	20	71±0	35	0.4 ±0.3	0.2	0.25±0	0.9± 0.9	.1	29	29
Se	5 ± 4.5	12±0	0.3±0	20	46	4±0	16	0.6 0.9	2.2	0.25±0	0.3± 0	1.		
Mo	16.3± 8	17±0	0.5±0	33	34.2	18±0	35	0.6± 0.3	1.3	0.5±0	0.5± 0	1		3
Ag	6.6 ± 5	15±0	1±0	6.6	14.5	40±0	40	3.9±8.3	4	1.0±0	1.5± 1.	1		
Cd	1.2 ± 1	24±0	2.6±0	0.5	9.5	30±0	12	2.55±0.0	1	2.55±0	2.6± 0	1	0.8	0.8
Sn	736±1144	238±0	1.5±0	491	158.5	740±0	493	1011±1709	674	5.5±0	2.8 ±3.7	3.7		
Sb	500±800	204±0	1.4±0.4	357	145.4	382±0	273	18±22	13	1.1±0	1.2±0.4	0.8		
Te	1.5 ± 0	1.5±0	1.5±0	1	1.0	1.5±0	1	1.50±0	1	1.5±0±0	1.5 ± 0.0	1		
Ba	3981±5740	3906±0	60±8.8	66	65	992±0	16.5	227±105	4	170	117±78	2.8	200	160
Hg	0.8 ± 0.7	0.5±0	18.5±1	0.04	0.03	0.5±0	0.0	0.54±2	0.03	1.0±0	0.5 ± 0.8	0.1	0.3	0.3
Ti	4845±2142	2608±0	8314±373	0.6	0.3	4969±0	0.6	3500±1059	0.4	5488±0	5187±1440	0.6		
Pb	3810±4333	2271±0	0.5±0.0	7620	4542	3770±0	7540	529±955	1058	34±0	26 ±22	68.8	85	85
Ta	0.5±0	1±0	29±18	367	0.03	1±0	0.0	15±8	0.5	22±0	18 ±3.5	0.7		
Fe	54873±7850	70090±0	21710±9659	2.5	3.2	97260±0	4.5	20265±7459	0.9	17780±0	15274±6909	0.8		
Mn	430±46	540±0	257±3.5	1.7	2.1	654±0	2.5	288±45	1.1	274±0	230±94	1.1		
PLI				**168.6**	**131**		**205**		**9**			**1.4**		

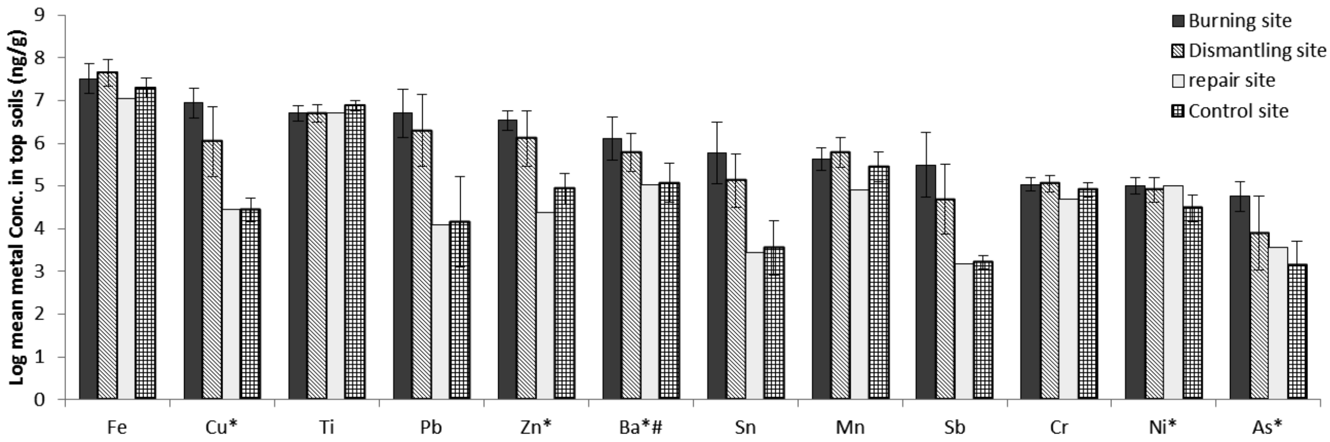
CF= Contamination factor/exceedance, PLI= Pollution Load Index, NSGV= Nigerian Standard Guideline Values, BS= Burning sites, DS=Dismantling sites, RS= Repair sites, CS= control sites

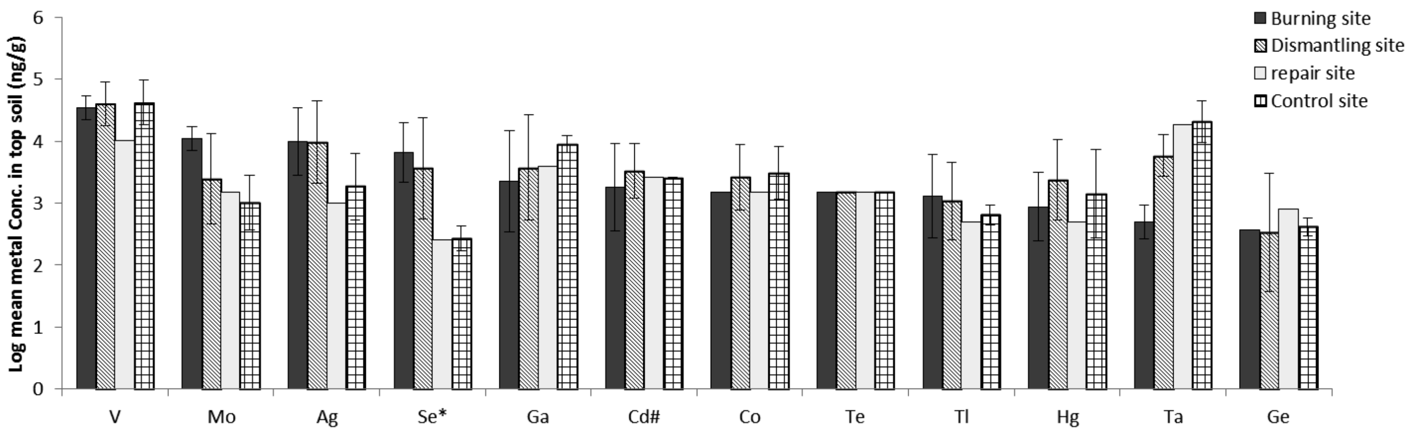
Supplementary Table S4.5: F-values of the Two-way ANOVA for Metals in Top Soils across the Locations and Activity Sites

	Metal	Location(ŋ)	Activity site(ŋ)	Location # Activity site(ŋ)
Soil (Burning, Dismantling, Repair, and Control)	V	1.297(0.110)	0.710(0.092)	0.344(0.062)
	Cr	1.878(0.152)	2.118(0.232)	1.900(0.266)
	Co	0.733(0.065)	0.527(0.070)	0.429(0.076)
	Ni	0.062(0.006)	5.164(0.425)**	1.025(0.163)
	Cu	0.383(0.035)	15.542(0.689)***	0.655(0.111)
	Zn	0.777(0.069)	10.636(0.603)***	0.660(0.112)
	Ga	0.318(0.029)	0.681(0.089)	0.103(0.019)
	Ge	0.084(0.008)	0.590(0.078)	0.875(0.143)
	As	0.276(0.026)	4.542(0.394)*	0.424(0.075)
	Se	2.031(0.162)	7.589(0.520)***	1.553(0.228)
	Mo	0.743(0.066)	2.578(0.269)	1.053(0.167)
	Ag	0.513(0.047)	2.642(0.274)	0.559(0.096)
	Cd	0.214(0.022)	1.054(0.131)	2.952(0.360)*
	Sn	1.890(0.153)	17.335(0.712)***	1.580(0.231)
	Sb	0.018(0.002)	12.596(0.643)***	0.788(0.130)
	Te	-	-	-
	Ba	1.108(0.095)	7.638(0.522)**	2.848(0.352)*
	Hg	0.471(0.043)	0.526(0.070)	2.794(0.347)
	Ti	1.119(0.096)	0.139(0.019)	0.159(0.029)
	Pb	6.735(0.391)***	20.778(0.748)***	2.601(0.331)
	Ta	0.177(0.017)	4.182(0.374)*	0.268(0.048)
	Mn	1.908(0.154)	1.637(0.190)	0.894(0.146)
	Fe	5.157(0.329)*	2.191(0.238)	1.114(0.175)

*** =p<0.000, **=p<0.001, *=P<0.05, ŋ=partial Eta squared, #= interaction effect

Supplementary Figure S4.1a : Relative Metal Distribution in Top Soils across the Sites





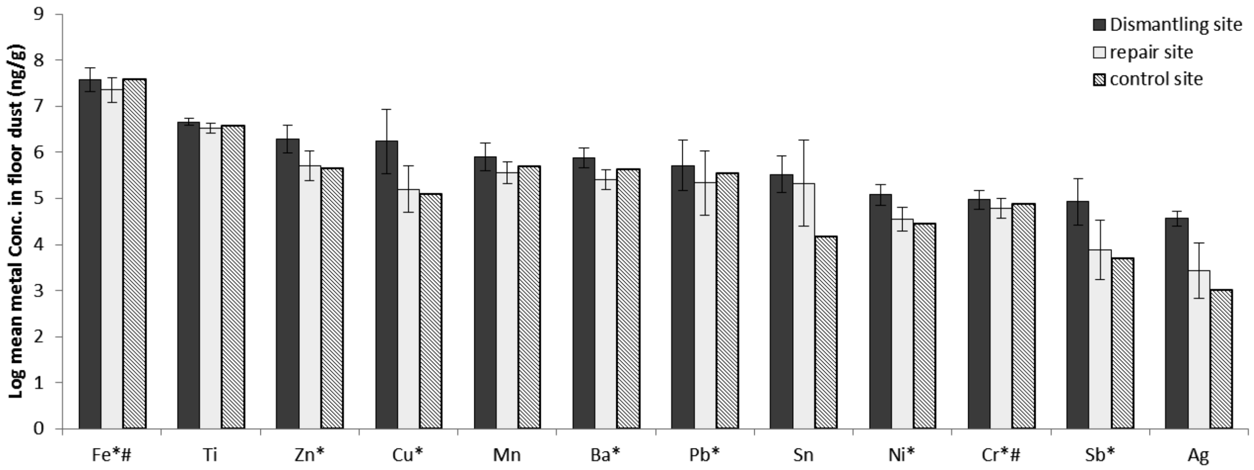
Supplementary Figure S4.1b: Relative Metal Distribution in Top Soils across the Sites

Supplementary Table S4.6: F-values of the Two-Way ANOVA for Metal Concentration in Floor Dusts across the Locations and Activity Sites

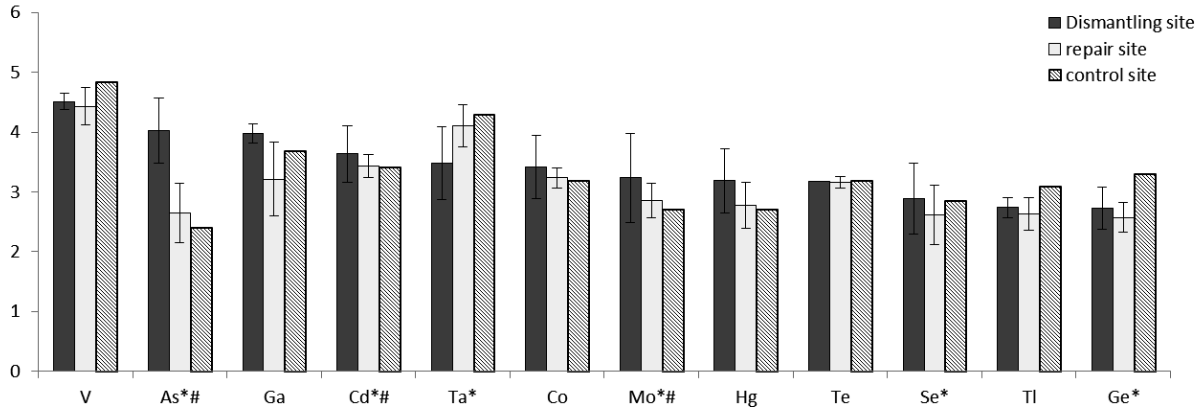
	Metal	**Location(η)**	**Activity site(η)**	**Location # Activity site(η)**
Floor dust (Dismantling and Repair)	V	16.949(0.566)***	1.189(0.084)	0.020(0.001)
	Cr	27.905(0.682)***	16.137(0.544)***	9.000(0.257)**
	Co	1.350(0.094)	0.542(0.040)	0.733(0.027)
	Ni	1.840(0.124)	9.706(0.427)***	1.243(0.046)
	Cu	4.982(0.277)**	13.190(0.504)***	1.769(0.064)
	Zn	14.458(0.527)***	21.499(0.623)***	3.291(0.112)
	Ga	0.030(0.002)	3.071(0.191)	0.458(0.017)
	Ge	2.683(0.171)	2.585(0.166)**	0.933(0.035)
	As	0.968(0.069)	17.394(0.572)***	4.849(0.157)*
	Se	6.760(0.342)***	3.549(0.214)*	2.391(0.084)
	Mo	7.681(0.371)**	10.140(0.001)***	10.995(0.297)**
	Ag	0.739(0.054)	7.265(0.358)**	0.285(0.011)
	Cd	9.834(0.431)***	10.230(0.440)***	24.653(0.487)***
	Sn	2.154(0.142)	2.228(0.146)	0.053(0.002)
	Sb	3.342(0.205)	8.292(0.389)**	0.591(0.022)
	Te	0.238(0.018)	0.081(0.006)	0.161(0.006)
	Ba	8.993(0.409)***	17.025(0.567)***	0.725(0.027)
	Hg	1.265(0.089)	0.394(0.029)	0.859(0.032)
	Ti	0.341(0.026)	2.888(0.182)	0.028(0.001)
	Pb	6.471(0.332)**	3.460(0.210)*	1.617(0.059)
	Ta	1.202(0.085)	5.145(0.284)*	0.886(0.033)
	Mn	13.995(0.518)***	8.312(0.390)***	0.396(0.015)
	Fe	23.522(0.644)***	12.443(0.489)***	4.749(0.159)*

*** =p<0.000, **=p<0.01, *=P<0.05, η=partial Eta squared, #= interaction effect

Supplementary Figure S4.2a and b: Relative Distribution of Metal concentrations in Floor Dusts from the E-waste Sites



Supplementary Figure S4.2 b: Relative Distribution of Metal concentrations in Floor Dusts from the E-waste Sites (Cont.)



Supplementary Table 4.7: Indepedent t-test

Lagos			Aba				Ibadan	
Metals	Comparing roadside dusts from dismantling and control sites in Lagos		Comparing roadside dusts from repair and control sites in Aba		Comparing roadside dusts from control sites and floor dust from repair sites and in Aba		Comparing direct dust from the electronic devices from repair sites/shops and floor dust from repair sites in Ibadan	
	t-values	**p-value**	**t-values**	**p-value**	**t-values**	**p-value**	**t-values**	**p-value**
V	0.996	0.393	0.723	0.488	0.243	0.811	-2.645	0.023*
Cr	0.361	0.742	-0.413	0.689	1.493	0.155	0.486	0.637
Co	0.390	0.722	-	-	-	-	-1.497	0.162
Ni	0.988	0.396	0.141	0.891	2.968	0.009*	-2.439	0.033*
Cu	6.180	0.009*	-0.096	0.926	5.267	0.000*	0.369	0.719
Zn	3.563	0.038*	0.429	0.678	4.992	0.000*	-0.539	0.600
Ga	1.102	0.351	0.361	0.727	-2.282	0.036*	-2.462	0.032*
Ge	3.331	0.045*	-1.336	0.214	-2.636	0.018*	-0.358	0.727
As	3.256	0.047*	-0.354	0.731	1.665	0.115	-2.203	0.050*
Se	11.543	0.001*			0.703	0.492	0.741	0.474
Mo	-	-			1.679	0.113	-1.008	0.335
Ag	1.468	0.238	-0.343	0.740	0.472	0.643	-1.190	0.259
Cd	-	-	1.753	0.114	0.000	1.000	0.302	0.768
Sn	3.048	0.056	1.292	0.229	5.570	0.000*	1.958	0.076
Sb	2.384	0.097	-0.33	0.975	3.935	0.001*	-0.680	0.511
Te	-	-	-		-	-	-	-
Ba	3.795	0.032*	0.554	0.593	1.837	0.085	-0.315	0.758
Hg	-2.107	0.126	3.317	0.009*	0.718	0.483	-1.642	0.129
Ti	0.450	0.683	0.318	0.757	_2.897	0.011*	-2.391	0.036*
Pb	6.738	0.007*	0.742	0.477	3.868	0.001*	1.374	0.197
Ta	0.693	0.538	1.027	0.331	-1.274	0.221	-3.554	0.005*
Mn	1.611	0.206	0.535	0.606	1.695	0.109	-1.494	0.163
Fe	1.880	0.157	0.479	0.644	1.514	0.149	-1.697	0.118
	Equal variance assumed, Df=2		Equal variance assumed, Df=9		Equal variance assumed, Df=16		Equal variance assumed, Df=9	
*= metals that had significant difference								

Supplementary Table S4.8: F-values of the Two-way ANOVA for Metal Concentrations in all sample across the various Locations at Dismantling Sites

	Metal	Location(η)	Type of sample(η)	Location # Type of sample(η)
All samples at Dismantling sites in the three locations	V	0.060(0.007)	4.749(0.456)**	0.304(0.018)
	Cr	2.650(0.238)	8.303(0.594)***	0.204(0.012)
	Co	0.204(0.023)	2.013(0.262)	0.002(0.000)
	Ni	0.548(0.061)	1.443(0.203)	0.234(0.014)
	Cu	1.818(0.176)	1.439(0.203)	0.002(0.000)
	Zn	1.055(0.110)	0.958(0.145)	0.066(0.004)
	Ga	0.546(0.060)	0.400(0.066)	0.015(0.001)
	Ge	0.921(0.098)	1.897(0.3251)	0.072(0.004)
	As	1.726(0.169)	0.683(0.108)	0.006(0.000)
	Se	5.902(0.410)**	1.845(0.246)	0.306(0.018)
	Mo	2.509(0.228)	0.202(0.034)	0.015(0.001)
	Ag	0.042(0.005)	1.392(0.197)	0.017(0.001)
	Cd	7.265(0.461)**	0.045(0.008)	0.005(0.000)
	Sn	0.665(0.073)	4.180(0.425)*	0.005(0.000)
	Sb	1.135(0.118)	1.765(0.238)	0.012(0.001)
	Te	-	-	-
	Ba	2.132(0.201)	1.641(0.225)	1.919(0.101)
	Hg	0.962(0.102)	2.565(0.312)	0.025(0.001)
	Ti	1.364(0.138)	14.162(0.714)***	3.893(0.186)
	Pb	4.384(0.340) **	10.240(0.644)***	0.053(0.003)
	Ta	0.582(0.064)	0.298(0.050)	0.064(0.004)
	Mn	0.074(0.009)	0.772(0.120)	0.002(0.000)
	Fe	2.172(0.204)	1.227(0.178)	0.122(0.007)

*** =p<0.000, **=p<0.001, *=P<0.05, η=partial Eta squared, #=interaction effect

Supplementary Table S4.9: F-values of the Two-way ANOVA for Metal Concentrations in all sample across the various Activity Sites in Aba

	Metal	Activity site(η)	Type of sample(η)	Activity site # Type of sample(η)
All samples (Burning, Dismantling, Repair, and Contol)	V	0.411(0.061)	0.424(0.043)	0.155(0.008)
	Cr	9.082(0.589)***	2.793(0.227)	0.049(0.003)
	Co	-	-	-
	Ni	25.795(0.803)***	1.201(0.112)	0.143(0.007)
	Cu	27.462(0.813)***	2.168(0.186)	1.158(0.057)
	Zn	21.564(0.773)***	1.025(0.097)	1.102(0.055)
	Ga	1.270(0.167)	0.166(0.017)	0.916(0.046)
	Ge	1.104(0.148)	0.029(0.003)	0.119(0.006)
	As	25.084(0.798)***	1.021(0.097)	1.391(0.068)
	Se	15.247(0.707)***	0.526(0.052)	1.054(0.053)
	Mo	154.807(0.961)***	0.112(0.012)	0.054(0.003)
	Ag	6.152(0.493)**	0.447(0.045)	0.055(0.003)
	Cd	33.892(0.843)***	0.065(0.007)	0.083(0.004)
	Sn	4.114(0.394)*	1.509(0.137)	0.609(0.031)
	Sb	10.046(0.613)***	1.179(0.110)	0.244(0.013)
	Te	-	-	-
	Ba	2.679(0.297)*	0.185(0.019)	0.200(0.010)
	Hg	24.881(0.797)***	26.398(0.735)***	32.914(0.634)***
	Ti	1.573(0.199)	0.042(0.004)	6.996(0.269)**
	Pb	25.706(0.802)***	2.938(0.236)	4.769(0.201)*
	Ta	11.544(0.646)***	0.140(0.015)	0.590(0.030)
	Mn	3.017(0.323)	0.144(0.015)	0.287(0.015)
	Fe	6.453(0.505)**p=0.003	0.355(0.036)	0.621(0.032)

*** =p<0.000, **=p<0.001, *=P<0.05, η=partial Eta squared, #=interaction effect

Supplementary Table S4.10: F-values of the two-Way ANOVA for Metal Concentrations in all sample across the various Locations at Dismantling Sites

	Metal	Location(η)	Type of sample(η)	Location # Type of sample(η)
All samples at Dismantling sites in the three locations	V	0.059(0.007)	0.076(0.009)	0.299(0.017)
	Cr	2.650(0.238)	1.085(0.113)	0.204(0.012)
	Co	0.176(0.020)	0.021(0.002)	0.007(0.000)
	Ni	0.546(0.060)	0.119(0.014)	0.231(0.013)
	Cu	1.818(0.176)	0.506(0.056)	0.002(0.000)
	Zn	1.055(0.110)	0.061(0.007)	0.066(0.004)
	Ga	0.566(0.062)	0.030(0.003)	0.006(0.000)
	Ge	0.921(0.098)	1.877(0.181)	0.072(0.004)
	As	1.726(0.169)	0.404(0.045)	0.006(0.000)
	Se	5.902(0.410)	0.096(0.011)	0.306(0.018)
	Mo	2.619(0.236)	0.211(0.024)	0.022(0.001)
	Ag	0.042(0.005)	1.355(0.137)	0.017(0.001)
	Cd	7.265(0.461) **	0.035(0.004)	0.005(0.000)
	Sn	0.665(0.073)	1.016(0.107)	0.005(0.000)
	Sb	1.135(0.118)	0.751(0.081)	0.012(0.001)
	Te	-	-	-
	Ba	2.132(0.201)	0.234(0.027)	1.919(0.101)
	Hg	0.962(0.102)	3.302(0.280)	0.025(0.001)
	Ti	1.364(0.138)	0.363(0.041)	3.893(0.186)
	Pb	4.384(0.340) **	0.022(0.003)	0.053(0.003)
	Ta	0.655(0.072)	0.332(0.038)	0.083(0.005)
	Mn	0.074(0.009)	0.451(0.050)	0.002(0.000)
	Fe	2.172(0.204)	0.130(0.015)	0.122(0.007)

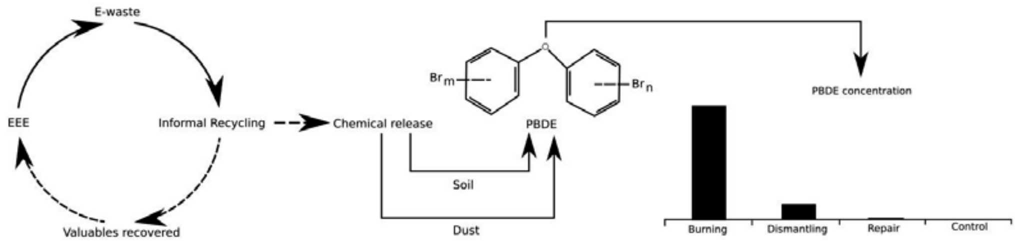
*** =p<0.000, **=p<0.001, *=P<0.05, η=partial Eta squared, #=interaction effect

Chapter 5

Polybrominated Diphenyl Ethers (PBDEs) Concentrations in Soils and Dusts at Informal Electronic Waste Recycling sites

Chimere May Ohajinwa*, Peter M. van Bodegom, Jingwen Chen, Qing Xie, Martina G. Vijver, Oladele Osibanjo, Willie J.G.M. Peijnenburg

(Submitted)



Graphical Abstract

Abstract

Concerns about the adverse consequences of informal electronic waste (e-waste) recycling is increasing, because e-waste contains some hazardous substances such as Polybrominated Diphenyl Ethers (PBDEs) which is used as flame retardants in electronics. There is dearth of information on the concentrations of PBDEs and the pattern of distribution at the various e-waste recycling sites in Nigeria. This study therefore measured the concentrations of 17 PBDE congeners, in top soils (0-10cm) and in various dust samples (floor dusts, roadside dust, and direct dust from electronics) from different e-waste recycling sites (burning, dismantling, repair). PBDEs concentrations at e-waste sites were compared with the concentrations in samples from corresponding control sites in three study locations in Nigeria (Lagos, Ibadan, and Aba).

There were significant differences in the level of PBDEs congeners between each of the e-waste recycling sites and the corresponding control sites. The levels of PBDEs at the e-waste recycling sites exceeded the levels at the controls sites by a factor of 100s to 1000s. In general, PBDEs concentrations at the e-waste sites decreased with the intensity of the e-waste recycling activities: burning sites > dismantling sites > repair sites > control sites. Our results suggest that the informal e-waste recycling has negative impacts on the enviroment and human health. Our findings provide a scientific basis crucial for devising more appropriate strategies to enforce e-waste management regulations in the informal sector without distrupting the e-waste workers' livelihood.

5.1. Introduction

Across the globe, electronic or electrical devices have become indispensable in our daily lives and the use of electronic electrical device is growing at great speed. It is characterized by an increasing number of users and rapid technological advances driven by efficiency, social and economic development. Many people now own multiple personal electronic devices such as information and communication technology (ICT) devices, but the life span of these devices are getting shorter mainly because they become obsolete more quickly compared to the past. In addition, most of these devices are disposed even before they become dysfunctional so as to make space for newer devices with better specifications/ functions. The exponentially growing demand for electronic equipment has led to a rapid increase in the rate of electronic waste (*e*-waste) generated. *e*-waste, also known as Waste Electrical and Electronic Equipment (WEEE), is one of the fastest growing municipal waste streams (Baldé *et al*., 2015). In 2016, 44.7 million metric tonnes (Mt) of *e*-waste were generated globally, and this amount is expected to increase to 52.2 million metric tonnes by 2021 (Baldé *et al*., 2017).

The concern about e-waste is not only about the volumes generated but also about the unsafe methods used in recycling the electronics, mainly in developing countries. *e*-waste contains over 1000 different substances, some of which are hazardous elements such as metals - lead, mercury, cadmium, arsenic, beryllium, and flame retardants such as Polybrominated diphenyl Ethers (PBDEs) (UNEP-DTIE. 2007, Widmer *et a*l., 2005). These mixtures of different substances, covering both chemicals present in EEE components and mixtures of chemicals released during *e*-waste processing, may pose significant implications for human health and environmental safety (Brigden *et al*., 2008; Asante *et al*., 2012).

PBDEs are a class of persistent organic pollutants (POPs) which have been used as flame retardants in many consumer products such as electronic equipment, textiles, furniture, automobile seats and other consumer products since the 1970s. PBDEs are a class of additive brominated flame retardants (BFRs), which are not covalently bound to the products (polymer matrices). In case of a fire, bromine radicals are released as a result of thermal energy. These radicals decrease the flame, and they reduce heat and carbon monoxide production. Because the PBDEs are not permanently bound to the polymer matrices, they are widely dispersed in the environment. In total, PBDEs has 209 congeners, which is dependent on the number and position of the bromine atoms on the two-phenyl rings. Approximately 56,418 metric tons of PBDEs were produced globally in 2003 (U.S EPA, 2010). PBDEs have mostly been produced and used in three commercial groups: pentabromodiphenyl ether (penta-BDE; $C_{12}H_5Br_5O$), octabromodiphenyl ether (octa-BDE; $C_{12}H_2Br_8O$), and decabromodiphenyl

ether (deca-BDE; $C_{12}Br_{10}O$) with about 11%, 6%, and 83% of global PBDEs respectively (U.S EPA , 2010, Kostianoy *et al*., 2010).
PBDEs are highly persistent in the environment, bioaccumulative in food chain and have a high potential for long-range environmental transport, meaning they can deposit far from their source. These chemicals have been detected in humans and in increasing concentrations in various environmental matrixes, including air, water, soil, sediment, animals and foods in all regions of the world. There is evidence of harmful effects in humans and wildlife, which includes endocrine disruption, immunotoxicity, reproductive toxicity, effects on fetal/child development (ATSDR, 2004), Zhang *et al*.,2016, Berg *et al*., 2013), thyroid and neurologic function (Koibuchi & Yen, 2016), and cancer (Darnerud *et a*l., 2001). Due to the environmental and health concerns, penta-BDE and octa-BDE have been banned in the European Union and voluntarily phased out in the USA since 2004 (Betts 2008,La Guardia *et al*., 2006). Recently, the European Commission restricted use of deca-BDE (EU, 2017). PBDEs are listed as persistent organic pollutants (POPs) by the Stockholm Convention (UNEP 2009), while deca-BDE (BDE-209) has been classified as a possible human carcinogen by the United States Environmental Protection Agency (US EPA 2010). Due to the ban on PBDEs, a number of alternative flame retardants has been introduced, which include: organophosphates esters (OPEs) and a range of other brominated and chlorinated novel flame retardants such as tetrabromobisphenol-A (TBBPA), hexabromocyclododecane (HBCD), bis(2,4,6,-tribromphenoxy) ethane (BTBPE), and several phosphate based compounds, such as triphenyl phosphate (U.S EPA, 2005,Lowell 2005, Pakalin *et al*. 2007, Castro-Jiménez *et al*., 2016, Li *et al.*, 2017).

Importation of electronics is one major way PBDEs are exported to developing countries such as China (Widmer *et al*., 2005), India (Awasthi & Li, 2017), Ghana, and Nigeria(Prakash and Manhart 2010; Ogungbuyi *et al*. 2012). When e-wastes are informally recycled using crude methods such as manual dismantling, smelting, and open burning which leads to incomplete combustion. Consequently mixtures of hazardous chemicals (including PBDEs) are released; these chemicals cause environmental pollution and health problems. PBDEs as additive flame retardants are more easily released into the environment than the reactive flame retardants. When released they are attached to particles and transported via various environmental media to distances far from the emission sites. PBDEs enter the environment through multiple pathways, such as emission during manufacturing, from products in use, from combustion, by leaching from landfills, or from recycling of products at the end of their life such as electronics at end-of-life (e-waste) (Darnerud *et al*., 2001). In the environment, soil and dust are the main receptors of chemical emissions from informal e-waste recycling. Therefore, soils can be secondary sources of emission of PBDEs and soils can contribute to the contamination of air and (drinking) water. Therefore, soils and dust are the most important environmental media that can reveal the contaminants present in the environment (Leung *et al*., 2008). Moreover, dust is a good indicator for contaminant levels in the atmosphere (Ackah 2017, Banerjee 2003,Wuana and Okieimen 2011,Tang *et al*., 2015, Xu *et al*. 2015,Tang *et a*l., 2013, Wuana and Okieimen 2011, Lu *et al*., 2014).

To gain insight into the PBDE concentrations in the environment as a result of informal e-waste recycling activities we systematically collected soil and dust samples from different selected e-waste recycling sites and from corresponding control sites in three cities where e-waste is recycled in Nigeria. Hence, the objectives of this study were to (1) quantitatively assess PBDE levels in top soils and dust because of different e-waste recycling activities (burning, dismantling, and repair sites) (2) determine the extent to which PBDE concentrations at e-waste sites exceeded the concentrations at control sites (3) determine the activities that contribute most to the PBDE pollution to the environment, and (4) determine the distribution patterns of the various PBDE congeners. Most importantly, we hope that our findings could be a wake-up call to relevant stakeholders to devise effective interventions to reduce PBDE pollution caused by informal *e*-waste recycling without impeding the livelihood of the *e*-waste workers. Our findings are likely to be applicable to other locations or countries where informal e-waste recycling is practiced.

5.2. Methods

5.2.1 Study Locations and Sites

The study was conducted in three study locations/cities (Ibadan, Lagos, and Aba) in Nigeria (figure 5.1 shows map of the study locations). In Lagos, the selected sites were Computer village, Ikeja (6.593ºN, 3.342ºE) and Alaba international market Ojor (6.462ºN, 3.191ºE). Alaba international market is the largest market for new and second-hand electronics in West Africa, with approximately ten to fifteen containers arriving daily from Europe and Asia, with each container containing about 400,000 second-hand units (Osibanjo & Nnorom, 2007). Computer village Ikeja is a popular place where electronics and their parts (new and second hand) can be purchased and repaired. In Ibadan, the selected sites were Ogunpa (7.383ºN, 3.887ºE) and Queens Cinema areas (7.392ºN, 3.883ºE). Ogunpa area is known for its activities in scrap/second-hand businesses, including electronics, while Queens cinema is known for sales and repair of both new and second-hand electronics. In Aba, the shopping centre (5.105ºN, 7.369ºE) and Port-Harcourt Road/Cementary (5.104ºN, 7.362ºE) and Jubilee road/St Michael's Road (5.122ºN, 7.379ºE) were selected. The shopping center area is the biggest market for new and used electronics, while the Port-Harcourt road/Cemetery area is known as an area for scrap/second-hand metal businesses in Aba. In Alaba, Lagos, we found only one big e-waste burning site, which is the largest, oldest, and most studied e-waste burning and dismantling site in Nigeria. In Ogunpa, Ibadan and Cemetery area Aba, the burning sites/spots were much smaller but more spread out in small clusters around the areas.

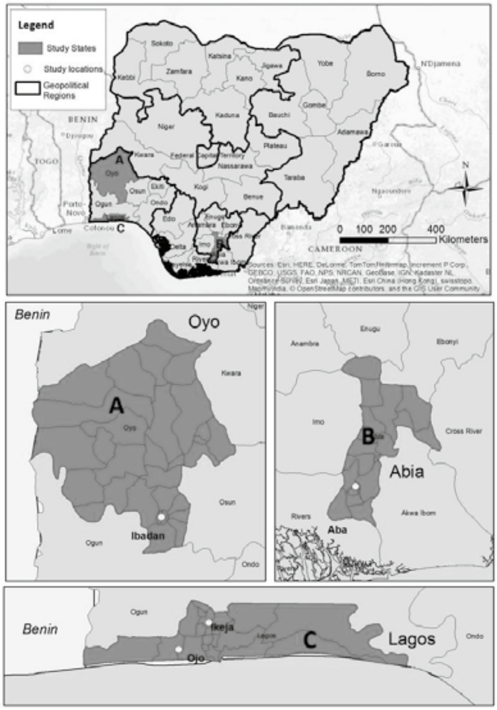


Figure 5.1. Map of Nigeria showing the Study Locations

5.2.2 Study Design

A comparative cross-sectional study design was adopted to gain an understanding of the level of PBDE pollution at the e-waste recycling sites compared with non-e-waste sites (control sites). In each study location, a multi-stage random systematic sampling technique was used to ensure inclusion of various e-waste recycling activities in the selected e-waste recycling areas. The control sites were between 100 to 500 meters away from the e-waste recycling sites, and consisted of areas with reduced human activity such as play grounds, parks, fields, and a university garden. Three types of e-waste recycling activities sites (burning sites, dismantling sites, and repair sites/shops) were analysed.

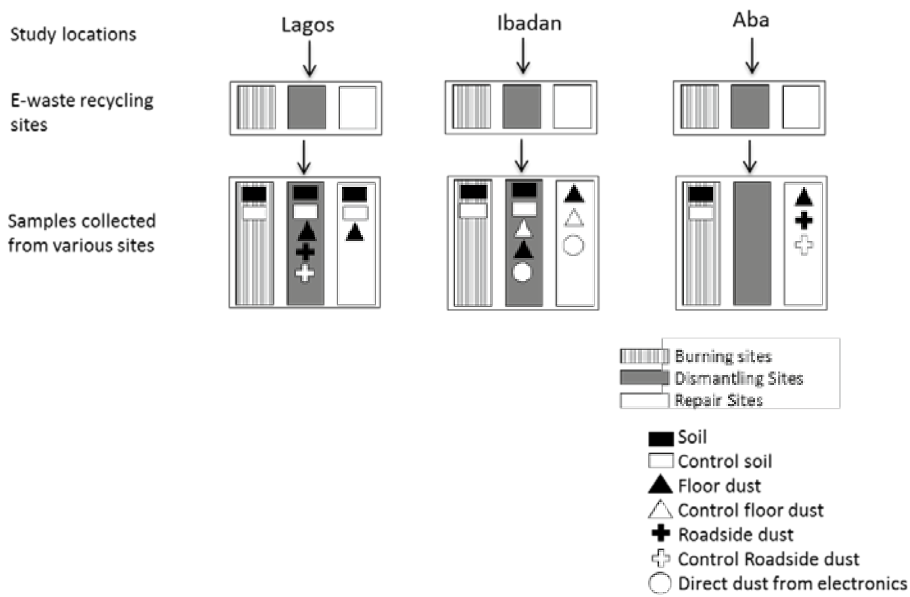


Figure 5.2. Schematic Flow Diagram of Sample Collection in the Study Locations

Top soils (0-10cm) and various dust samples were collected from the selected e-waste recycling sites. Type of sample collected depends on how feasible it is to collect the sample; this led to an unbalanced design in soil sample collection. At burning sites, only top soil samples were collected. Direct dust from the electronics, mainly from televisions, computers, printers, and air conditioners were also collected. The locations of the sampling spots were georeferenced using a global positioning system application on a phone. Figure 5.2 presents a schematic diagram of the sample collection from the various e-waste sites in the three study locations.

5.2.3 Sample Collection and Preparation

First, the amber bottles and aluminium foils were treated in the laboratory. The amber bottles were washed with tap water and laboratory detergent, rinsed with a copious amount of tap water, rinsed with distilled water 3 times, treated with acetone and with hexane, and then oven-dried at 120°C for 4 hours to ensure no traces of POPs were present. Aluminium foils (for soil wraps on the field) were treated with acetone and hexane, then oven dried at 120°C to ensure no traces of POPs in the aluminum foil.

On the field, for top soil (0-10 cm) collection, each selected site was divided into grids of about 2 m to 10 m wide, depending on the size of the site. Samples were systematically collected from 3 to 6 points within each site. The samples were bulked together for the top soil to form a composite representative sample for the specific site. Soil samples were collected using a soil auger, and a soil trowel was used to the transfer soil from the soil auger into aluminum foil (sample wraps). To avoid cross contamination, the soil probe/auger and trowel were decontaminated (cleaned first with a brush and wiped thoroughly with wet wipes) before each sample collection at each sampling site. Dust samples were collected using plastic brushes to gently sweep the dust and collect it with a dustpan. The soil and dust samples were wrapped in a treated aluminum foil, labelled, and transported to the laboratory. A total of 71 samples (56 samples from the e-waste recycling sites and 15 samples from control sites) were analysed. The total set consisted of 22 top soil (0-10 cm depth) samples, 30 floor dust samples, 13 roadside dust samples, and 6 direct dust samples. Soil and dust samples were air dried for 7 days, avoiding exposure to sunlight. The samples were homogenized, ground with a mortar and pestle, and sieved through a 1 mm mesh sieve to remove bigger particles. Next, they were transferred into individual 10 ml amber bottles, labelled and stored at -20°C until shipping to the laboratory for analysis. The samples were collected between May and November 2015.

5.2.4 Chemicals and Materials

All the solvents used for extraction, purification and analysis were of HPLC grade (Spectrum Chemical MFG. Corp., USA). Silica gel (100-200 mesh) and neutral aluminum oxide (100-200 mesh) were for chromatography purpose (Sinopharm Chemical Reagent Co., Ltd, China), and they were activated before use (i.e., first washed with hexane/dichloromethane (v/v, 1/1) and then baked at 180 °C for 2 hours). Acid silica gel (30% w/w) was prepared with activated silica gel and sulphuric acid before use. Anhydrous sodium sulfate (99% purity) and diatomaceous earth (DE, 100% purity) were purchased from Aladdin Ind. Corp, China and Thermo Fisher Scientific respectively. They were baked at 400°C for 4 hours before use to remove any traces of organic matter.

A standard mixture solution of 14 PBDE congeners (BDE-COC) PBDEs (BDE-17, BDE-28, BDE-71, BDE-47, BDE-66, BDE-100, BDE-99, BDE-85, BDE-154, BDE-153, BDE-138, BDE-183, BDE-190, and BDE-209) and Individual standards of 4 PBDEs (BDE-77, BDE-206, BDE-207, BDE-208) and PCB-209 were purchased from Accu Standard, while Isotopically labeled ^{13}C-PCB-208 was purchased from Cambridge Isotope Laboratories.

5.2.5 Sample Extraction and Cleanup

For the PBDE analysis, from each of the samples, 5g of homogenized sample was thoroughly mixed with 0.6g DE with a mortar and pestle. Each sample was thereafter spiked with 2ng ^{13}C- labeled PCB-208 and 10 ng PCB-209 standards, and allowed a static equilibration of 5 minutes in two cycles. The sample was then extracted using an ASE 350 accelerated solvent extraction system (Dionex, USA) with n-hexane/dichloromethane (v/v, 1/1) at 90ºC, 1500 psi. After extraction, acid washed copper sheets were added to the extracts to remove sulfur present in the samples. The extracts were evaporated to about 1.0 mL under a gentle stream of N_2, and transferred to a conical centrifuge tube. One mL of concentrated sulfuric acid (98%) was added to the concentrated extracts to carbonize part of the impurities present. The supernatants were transferred to a preconditioned glass cleanup column, which was packed with 0.5 cm neutral aluminum oxide, 3.0 cm neutral silica gel, 3.0 cm acid silica gel, and 1.0 cm anhydrous sodium sulfate from the bottom to the top. The columns were then eluted with 20 mL hexane, and the eluent was evaporated to about 0.3 ml and transferred to a 1.5 ml sample vial. After the internal standard (10 ng BDE-77) had been added to the vial, the volume of the solution was made up to 0.5 ml.

5.2.6 Sample Analysis

An Agilent 6890 GC/5975 MSD system operated in negative chemical ion source/ selective ion monitoring (NCI/SIM) mode and equipped with a 15 m DB-XLB column (0.25 mm, 0.1 µm film thickness, J&W) was used for PBDE separation and quantification. The samples (1 µL) were injected in split less mode. Helium was used as carrier gas at a flow rate of 1.2 mL/min, and the temperature program was set as follows: 90 °C for 2min, increased to 320 °C at 15 °C/min and held for 7 min. The temperature of GC inlet, transfer line, ionization source and quadrupole were set at 290°C, 300 °C, and 150 °C. The compounds were monitored at m/z 79 and 81 for 3-7 brominated BDEs, m/z 79, 81, 487 and 489 for BDE-206, 207, 208 and 209, m/z 474, 476 for ^{13}C-PCB-208, and m/z 497.6, 499.6 for PCB-209.

Soil pH was measured using a calibrated pH meter (691, Metrohm AG) in a weight: volume ratio of 1:10 of soil and tap water, adopting the USEPA method 9054D (USEPA, 2004). Total organic content (TOC) of the soil and dust was determined as the weight loss of dried soil (3 hours at 100 ℃) at 550 ℃ for 5 hours (Pansu & Gautheyrou, 2006). Since PBDEs have a great potential to bind to environmental matrices rich in organic carbon (Maya Li Wei-Haas, 2015), measuring the TOC concentration in the soil and dust samples was used to establish whether there was any correlation between the measured PBDE and TOC.

5.2.7 Quality Assurance/Quality Control

A meadow soil collected from a cropland in Liaoning, China (123.90^{o}E, 41.38^{o}N) which was tested and demonstrated to be free of most of the studied PBDEs, was used as matrix blank and matrix spike samples. Twenty ng BDE 206, 207, 208, 209 and 4 ng of the other target PBDEs were spiked into 5 g meadow soil to evaluate the method performance. The recoveries for BDE-100, 154, 153, 183, 190, 208, 207, 206 and 209 were 60-107 %. For BDE-28, 47, 66, and 99, the recoveries were 32-58 %.

For all the target compounds, the relative standard deviations of duplicate samples were less than 14 %. For the spiked surrogate ^{13}C-PCB-208 and PCB-209, the average recoveries in all samples were 71 % and 84 %, respectively. The method detection limits (MDLs) values characterized as 3 times signal-to-noise ratio were 8 – 164 pg/g for the target PBDEs. The procedural blanks and solvent blanks were analysed simultaneously with samples to check for interferences and contamination. The reported results of PBDEs in the samples were corrected by recoveries of ^{13}C-PCB-208. Three criteria were also used to ensure the correct identification of the target compounds (Zhu & Hites, 2006): (a) The GC retention times matched those of the authentic standards within ±0.1 min. (b) the signal-to-noise ratio was greater than 3:1; and (c) the isotopic ratios between the quantitative and confirmation ions were within ±15% of the theoretical values.

5.2.8 Data Analysis

A two-tailed Pearson correlation coefficient was used to determine the strength of association between PBDE congeners and Total Organic carbon (TOC). In this contribution, we considered 17 PBDE congeners – BDE-17, BDE-28, BDE-71, BDE-47, BDE-66, BDE-100, BDE-99, BDE-85, BDE-153, BDE-154, BDE-138, BDE-183, BDE-190, BDE-207, BDE-208, BDE-206, BDE-209. The PBDE concentrations were summarized using descriptive statistics (frequencies, median means, and standard deviations). In addition, the pollution status of the different sites were evaluated by calculating the ratio of various PBDE concentrations at the e-waste sites compared to the control sites, which is known as exceedance(Ex) or contamination factor(CF). A CF < 1 indicates low contamination, 1 < CF < 3 moderate contamination, 3 < CF < 6 considerable contamination and CF > 6 indicates a very high contamination level (Lars Hakanson, 1980) (Islam *et al.*, 2015).

To understand variabilities in the mean concentration distribution of PBDEs in the environmental samples, we evaluated the differences in the mean concentrations of the individual PBDE congeners and the sum of the PBDE congeners ($\sum_{17}$PBDE) by running a series of one-way (using activity site as factor on the log transformed data for soil, floor dust, roadside dust and direct dust separately.

Additional series of two-way ANOVAs were run, firstly with activity sites (burning, dismantling, repair, and control sites) and location as explanatory variables; secondly with type of activity/activity site and type of sample (soil and dust) as explanatory variables. Bonferroni posthoc tests were included to interpret the significant main effects of the ANOVA outputs. Principal component analysis (PCA) was used to evaluate whether variation in PBDE concentrations was similar across PBDE compounds. A p-value of 0.05 was considered statistically significant. All statistical analyses were performed using SPSS version 23.

5.3. Results

3.1 Physicochemical Characteristics of the Soil and Dust Samples

The soil texture in Lagos and Aba is sandy loam and in Ibadan sandy clay (Nkwunonwo & Okeke, 2013). The physiochemical characteristics of the soil and dust samples such as pH, organic matter content (TOC), are presented on table 5.1 and supplementary table 5.1. The pH at the burning sites ranged from 7.2 to 8.4, dismantling sites (1.9 to 9), repair sites (7.9 to 9.24), and control sites (7.4 to 9); while the TOC for the burning sites ranged from 8 to 36.3%, dismantling sites (1.6 to 24%), repair sites (1.14 to 24%), and control sites (0.98 to 5.3%). There were significant differences in the pH (p=0.004) and TOC (p=0.000) levels between all the sites. Also, there were significant differences in the pH (p = 0.006) and TOC (p = 0.00) between the various e-waste recycling sites. There was a correlation between the TOC and all the individual PBDEs and $\sum_{17}$PBDEs.

Table 5.1: Physicochemical parameters (mean of pH and Total Organic matter content) of the samples at the study locations. No standard deviation is given if n=1.

	Burning sites		Dismantling sites		Repair sites		Control sites	
	pH	**TOC%**	**pH**	**TOC%**	**pH**	**TOC%**	**pH**	**TOC%**
Soil	7.8 ± 0.43	20 ± 11	5.8 ± 3	7.4 ± 6.3	8.8	1.5	8.0 ± 0.4	3.2 ± 0.9
Roadside dust	-	-	8.3± 0.06	4.4 ± 2.6	8.1	1.5	8.3 ± 0.5	1.3 ± 0.3
Floor dust	-	-	8.4 ±0.24	5 ± 1.0	8.4 ± 0.3	4.1 ± 4.2	8.8	5.3
Direct dust	-	-	-	-	9 ± 0.2	17.4 ± 6	-	-

5.3.2 PBDE Concentrations at the various Activity Sites

PBDE concentrations at e-waste sites and control sites are presented in supplementary tables 5.2–5.4 and in figure 5.3. PBDE congeners were detected in all sampling sites, indicating that PBDEs were widespread pollutants in this research area. The total concentration ($\sum_{17}$PBDEs) ranged from 1.730 to 149,880.270 ng/g. The most abundant PBDE congener in all the sites and samples was BDE-209, with concentrations ranging from 0.850 to 147,091.400 ng/g. The maximum $\sum_{17}$PBDEs was found in direct dust from TV repair shops in Ibadan. The concentration of BDE-209 was 1.5 to 44 times higher than the summed concentrations of the other 16 PBDEs ($\sum_{16}$PBDEs). This high variability in PBDE concentrations is a reflection of the activities on the sites. The abundance of the PBDE congeners (considering the median of all the samples) in all the locations is generally in this order: BDE-209 > BDE-207 > BDE-206 > BDE-183 > BDE-208, BDE-99 > BDE-153 > BDE-71 > BDE-47 > BDE-190 > BDE-154 > BDE-100 >BDE-28 > BDE-66 > BDE-138 > BDE-85 > BDE-17. The PBDE concentrations at the e-waste sites exceeded the control sites by many folds, see figure 5.3 and supplementary tables 5.2-5.4. The general pattern of the PBDEs distribution at the e-waste sites showed concentrations in this decreasing order: burning sites > dismantling sites > repair sites > control sites. This shows that burning activities contribute most to the PBDE concentrations in the environmental matrices, as is also clear from the patterns in $\sum_{17}$PBDEs (figure 5.3). The $\sum_{17}$PBDE concentration in top soils at all the sites is in this order (burning > dismantling > repair), the highest concentration was in Lagos. The $\sum_{17}$PBDE concentration in floor dust was highest at repair sites in Ibadan, the $\sum_{17}$PBDE concentration in roadside dust was highest at dismantling sites in Aba.

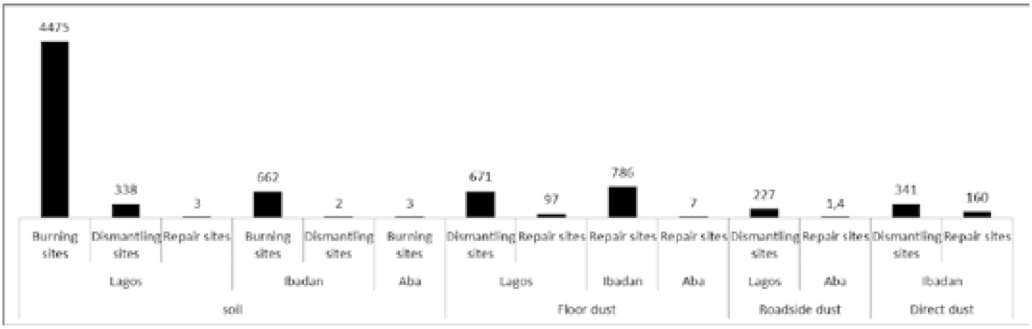


Figure 5.3. Exceedances of $\sum_{17}$PBDE concentrations in the samples from the e-waste recycling sites compared to the control sites across locations

5.3.2.1 Assessment of the top Soil Samples

The one-way ANOVAs showed a significant difference in the concentration of $\sum_{17}$PBDE and all the PBDE congeners, except BDE-28, in top soils between the activity sites, ($p=0.05$). Post hoc comparisons indicated significant differences between control and burning sites, and control and dismantling sites for all the PBDE congeners and $\sum_{17}$PBDE, see figure 5.4 and supplementary table 5.5.

While the type of activities on the sites influences the PBDE concentrations on the sites, that effect might differ across locations. To test this assumption, a two-way ANOVA was performed and this ANOVA confirmed a significant difference in all the PBDE concentrations (except BDE-17) between the activity sites, with the burning sites having the highest concentrations, followed by dismantling sites, then control sites. Forty-one to 100% of the variability in PBDE concentrations was accounted for by the activities at the sites. However, there was no significant difference in the concentration of any of the PBDE congeners between locations, except for BDE-28, 208, and 207. The PBDE concentrations were generally highest in Aba, followed by Lagos, then Ibadan. This excludes BDE-28, which is highest in Lagos. Also, the interaction of activities at the sites and location showed no significant difference on any of the PBDE congeners and $\sum_{17}$PBDE concentrations, except for BDE-28 (see supplementary table 5.6).

5.3.2.2 Assessment of the Floor Dust Samples

A one-way ANOVA showed a significant difference ($p=0.05$) in the concentration of some of the PBDE congeners (BDE-99, 47,100, 154, 190, 66, 138) in floor dust between dismantling and repair sites. (figure 5.4).The two-way ANOVAs testing individual PBDE congeners and total PBDEs ($\sum_{17}$PBDE) concentrations in floor dust from the activity sites (dismantling and repair sites) and across the locations (Lagos, Ibadan, and Aba), showed significant differences in the concentration of some PBDE congeners (except BDE-47, 66, 100, 99, 85, 154, 138, 190) between the activity sites, with dismantling sites having higher concentrations than repair sites. Also, there were significant differences in the concentration of some PBDE congeners (BDE- 47, 66, 100, 99, 85) between locations, with Ibadan having generally the highest PBDE concentrations, followed by Lagos, then Aba. The interactions of activities at the sites and location showed no significant difference on any of the PBDE congener and $\sum_{17}$PBDE concentrations, except for BDE-154 (see supplementary table 5.7)

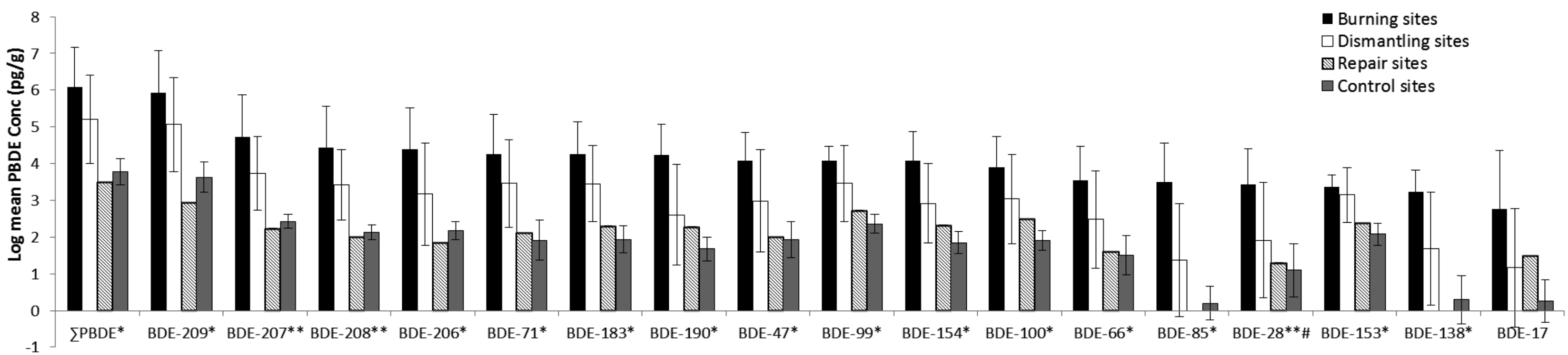


Figure 5.4. PBDE concentratio in top soils across the sites. The PBDE congeners influenced by activity at the sites are indicated with*, and an additional * for those influenced by location, and # for interaction between activity and location

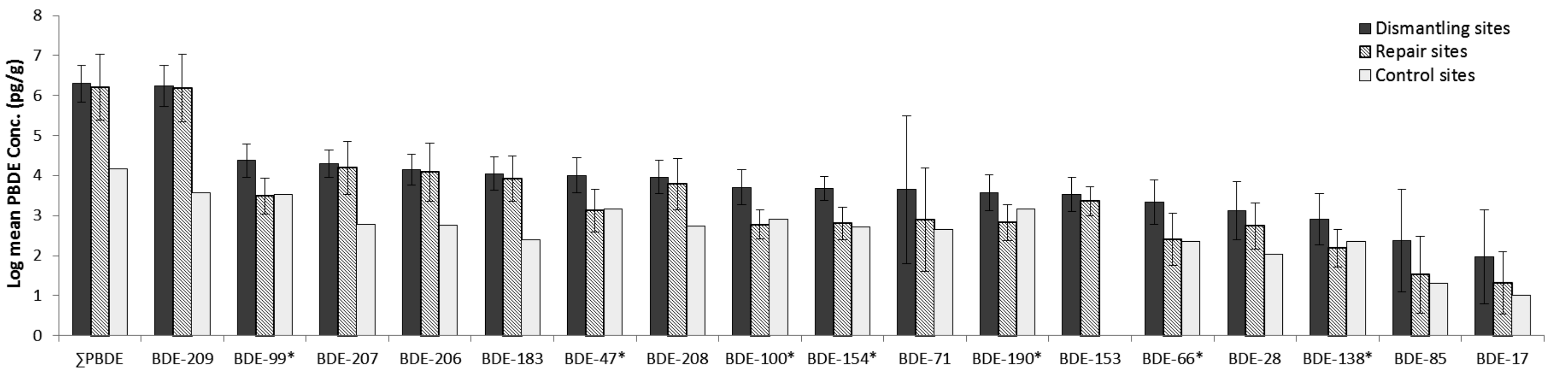


Figure 5.5. PBDE Concentration in Floor Dust across the Sites. The PBDE congeners influenced by activity at the sites are indicated with*

5.3.2.3 Assessment of the Roadside Dust Samples

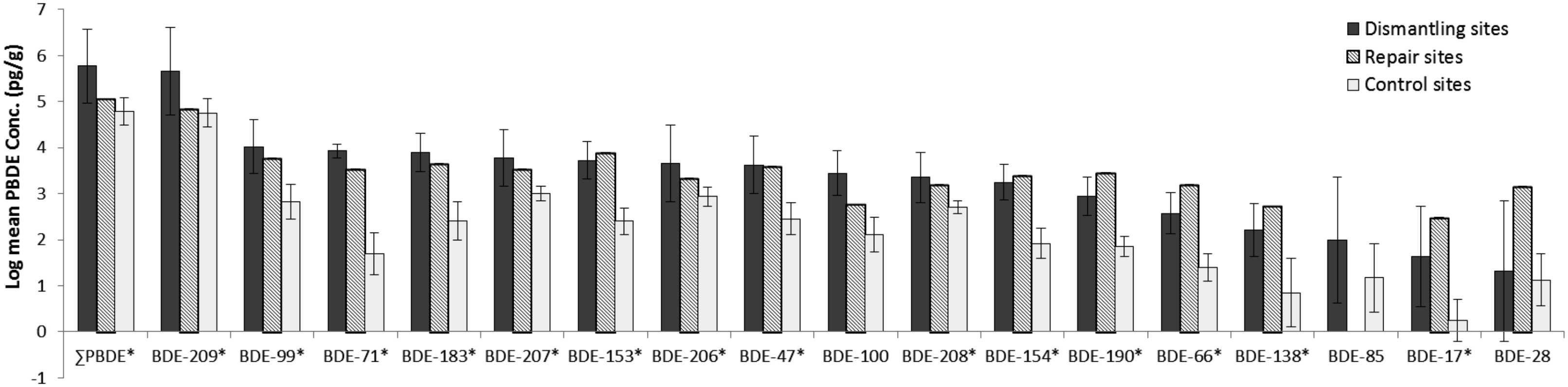


Figure 5.6. PBDE Concentration in Roadside Dust across the Sites. The PBDE congeners influenced by activity at the sites are indicated with*

Roadside dust samples were collected only from Lagos and Aba. One-way ANOVA showed a significant difference ($p=0.05$) in the concentration of almost all the PBDE congeners in roadside dust between dismantling and control sites (figure 5.6).

5.3.2.4 Assessment of the Direct Dust Samples

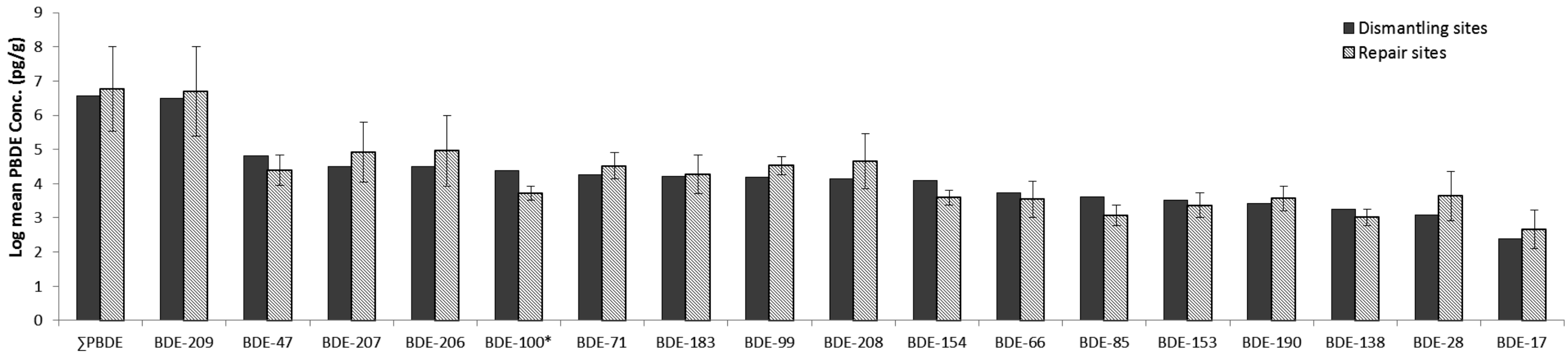


Figure 5.7. PBDE Concentration in Direct Dust from Electronics at the Sites. Generally, there were no significant differences in the PBDE concentrations, except for BDE-100.

Direct dust samples from electronics were collected from dismantling and repair sites from Ibadan only. A one-way ANOVA showed no significant difference in the concentration of any of the PBDE congeners in direct dust between dismantling and repair sites, except BDE-100, (figure 5.7).

5.3.4 Patterns in PBDEs Contamination

The PCA revealed one common axis of variation in PBDE concentrations, which accounted for 77% of the total variance. All PBDEs varied in the same direction (figure 5.8). These findings indicate that PBDE contamination has one common driver, which might suggest on common source. Figure 5.8 shows that the burning sites, followed by the dismantling sites containing more of the lower PBDE congeners which are more toxic, while the repair and control sites contain more of the higher molecular PBDEs. This further confirms that open opening as an e-waste recycling activity has the most negative impact. Pearson correlation confirmed that all PBDEs congeners at the e-waste sites strongly correlated positively with each other (supplementary table 5.5). The second axis explained 7% of the variance in PBDE concentrations. Interesting, type of sample separated along this second axis, with floor dust samples having positive values on the second axis, and soil having negative scores on the second axis.

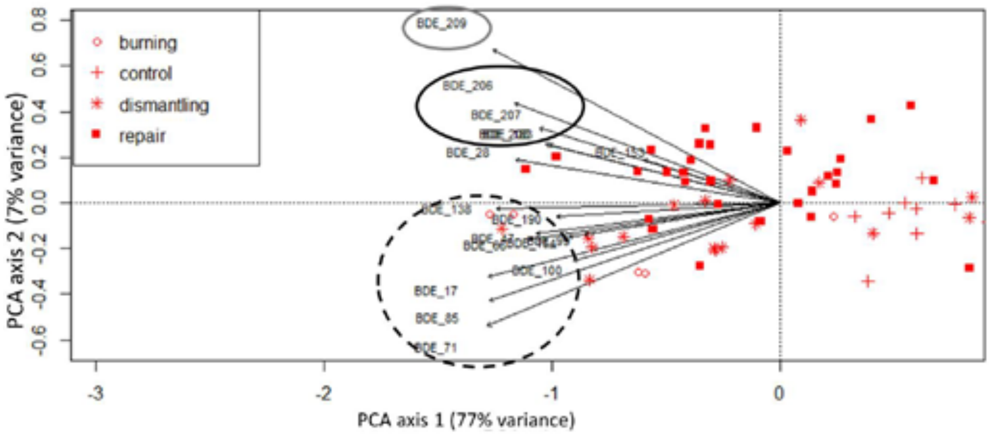


Figure 5.8: PCA Plot of PBDE Concentrations. Three groups pf commercial PBDEs: penta-BDE(- - - -), octa-BDE(——), and deca-BDE(——)

5.4. Discussion

In this study we analysed the PBDEs concentrations in soil and dust samples from different e-waste activity sites (burning, dismantling, and repair sites) as compared to corresponding control sites in three different cities in Nigeria. The strengths of this study are the analyses of the interrelationships between the e-waste sites and the environmental matrices such as top soils, floor dusts, roadside dust, and direct dust from the electronics in which PBDEs are measured. In addition, we employed systematic steps to selection of the sampling sites to ensure that various e-waste recycling activities are representated. These distinctions, we did not find in the previous studies.

Most *e*-waste recycling activities, especially at dismantling and burning sites are carried out outdoors. The recycling activities include storage, washing, cleaning, dismantling, and metal recovery through stripping of wires or open burning. The remains of e-waste materials from the recycling activities are dumped outside on the ground. Most repair activities, which involve soldering of various parts, take place indoors but also sometimes outdoors, depending on the settings of the work environment and the weather condition. These activities release large quantities of hazardous substances. Soils and dusts are a major repository for pollutants released into the environment by human activities, and they are important environmental media that can provide information about the level, distribution, and fate of contaminants present in the environment as a result of informal *e*-waste recycling.

Despite the increasing volumes of *e*-waste generated over the years, collection and recycling of e-waste are still not improved in developing countries (Ackah, 2017). Nigeria imports the largest volume of new and used electronic and electrical equipment in Africa (Ogungbuyi et al., 2012). The amount of e-waste generated in Nigeria increased from 219 kilo tonnes in 2014 (Baldé *et al.,* 2015) to 277 kilo tonnes in 2016 (Baldé *et al.,* 2017). The majority of the e-waste is recycled in an unsafe/informal manner (Ogungbuyi *et al*., 2012, Baldé *et al.,* 2017). This situation in Nigeria is likely to be representative for informal e-waste recycling in countries that lack the resources for safe e-waste recycling such as in India, Brazil, Mexico (Lundgren, 2012), and Ghana (Akortia *et al*., 2017) among others.

5.4.1 Extent of Pollution as a Result of Informal e-waste Recycling

Our findings revealed that open burning of *e*-waste is the most polluting *e*-waste recycling activity. This is in accordance with a study by Matsukami *et al*., (2017) which compared burning sites and other e-waste processing sites in Vietnam. PBDEs do not occur naturally in the environment, but

traces of PBDEs were found in control sites, indicating deposits of PBDEs in the environment not too far from e-waste recycling sites. These PBDEs might have been transported by wind/air to nearby vicinities, which is in agreement with the observations of decreasing concentrations of PBDEs with increasing distance from *e*-waste sites (Luo *et al*., 2012; Li *et al*., 2013)
In our study we included dust samples, considering that some of the activities (such as repair activities) do not take place on soil (bare ground) most of the time. The added value of determining the PBDE concentrations in the dust samples was to ensure that different types of e-waste activity sites were studied. Dust is one of the main sources of exposure to PBDE via inhalation or ingestion. Thus it provides information about the level of contaminants in the indoor atmosphere as well as the levels of contaminants to which the workers and the public are exposed. Dust also reflects the characteristics of short and long term activities in the area. Furthermore, the combination of soil and dust samples gives a comprehensive overview of the impact of informal e-waste recycling on the environment. It is likely that there is a cross transference of the PBDEs from the floor dust(indoor) from the shops to the soil, and from the soil from the burning and dismantling sites into the shops (contaminating floor dust). There is also a probable transfer of PBDE from the *e*-waste sites to locations farther away from the *e*-waste recycling sites, which is in agreement with the previous findings (Luo *et a*l., 2012, Li *et al*., 2014).

We found high concentrations of PBDE congeners at the *e*-waste sites with the higher molecular weight PBDEs (BDE-209, BDE-153, BDE-183) having the highest concentrations, and BDE-209 being the most abundant. Predominance of BDE-209 in samples is probably due to the fact that the deca-BDE mixture is the predominant PBDE still in use (Lowell 2005, Morf *et al*., 2005). This is in agreement with the results of previous studies in Turkey (Cetin, 2014), in five Asian countries (Matsukami *et al*., 2015; Li *et al*. 2016), in Vietnam by Matsukami *et al*., (2017), in Ghana by Akortia *et al*., (2017), and in Nigeria and China (Alabi *et al*., 2012). However, in a similar study in Ghana, BDE-28 was found to have the highest concentration instead of BDE-209 (Akortia *et al*., 2017). The maximum concentration of BDE-209 was 147,091 ng/g, as found in dust from a television. This is similar to the findings of (Li *et al*., 2014, Takigami *et al*., (2008) showing the highest concentrations of PBDEs (BDE-209) in dust from e-waste sites.

The PBDE present at the *e*-waste sites and the control sites reflects the pollution from anthropogenic sources in urban areas. Comparing the mean concentrations of BDE-209 levels in top soils to those reported in previous studies at the same study areas, it is found that BDE-209 concentrations are decreasing (table 5.2). This could be because PBDE has been banned, although the levels at burning sites The median BDE-209 concentrations at the burning sites is as high as 17587ng/g at Alaba, Lagos (supplementary tables 5.2-5.4). We compared BDE-209 because that was the PBDE congener is commonly analysed across the various studies. In this study we distinguished between PBDE levels at various e-waste recycling sites (burning, dismantling, and repair sites). These distinctions were not made in the other studies. Mean BDE-209 levels found at Alaba is higher than the level found in the widely studied area of Guiyu, China in 2014 and in China in 2015. Guiyu, China is known for its notorious intensive unregulated crude e-waste recycling activities. This shows that maybe more notorious e-waste recycling activity maybe going on somewhere in Nigeria, which are yet to be reported. These findings further show that the PBDEs concentration in urban cities in Nigeria is high and calls for attention. This consequently implies that more people in the general population that are not even *e*-waste workers might be exposed to PBDE. This is more disturbing as majority of the e-waste workers are unaware of the health risks associated with their jobs (Ohajinwa *et al*., 2017a) and do not use any form of PPE (Ohajinwa *et al*., 2017b) or take appropriate cause to protect their health or the environment.

Table 5.2: Comparison of Mean conc. of BDE-209 Concentrations in Soils at E-waste sites with other Studies

Countries	**Units**	**BDE-209**	**Reference**
Computer village Nigeria	ng/g dry wt	583	This study
Alaba international market, Nigeria (burning, dismantling, and repair sites)	ng/g dry wt	7648 ± 8369	
Alaba international market, Nigeria (burning sites)	ng/g dry wt	17587	
Alaba international market, Nigeria (dismantling sites)	ng/g dry wt	6502±7087	
Alaba international market, Nigeria (repair sites)	ng/g dry wt	0.850	
Soil at e-waste recycling site, Ghana	ng/g dry wt	10.6 ± 16.6	*Akortia et al., 2017*
Soils near e-waste recycling site, China	ng/g dry wt	3400 ± 4200	*Matsukami et al., 2015*
Soils near e-waste recycling site South Korea	ng/g dry wt	8.8 ± 11	
Soils near e-waste recycling site Vietnam	ng/g dry wt	63	
Guiyu Soils near e-waste recycling site, China	ng/g dry wt	1157 ± 1131	Zhang *et al.*, 2014
Computer village dumpsite soil, Nigeria	ng/g dry wt	1820	*Alabi et al., 2012*
Alaba international market dumpsite soil, Nigeria	ng/g dry wt	9800	
Guiyu e-waste dumpsite soil, China	ng/g dry wt	12130	

The mean concentration of ∑PBDEs at the control sites significantly differed from the various e-waste recycling sites. There was no significant difference in the PBDE concentrations between the locations, and between sample types for most of the PBDEs. These findings indicate that activities in the vicinity have impact on the level of PBDEs in an area. All PBDE congeners positively correlated with each other. The positive correlations between the PBDE congeners indicate that the PBDEs are likely from the same source with similar emission patterns. This was further confirmed by the PCA, in which 77% of the total variance of all PBDE congeners was accounted for by a common axis.

Although penta-BDE, octa-BDE, and deca-BBE are banned in developed countries where electronics are manufactured, and despite Nigeria having regulations on e-waste management which in turn controls PBDEs emissions, PBDEs were found in high concentrations at the *e*-waste sites and at the control sites, this shows that PBDEs are ubiquitos in Nigerian environment, as stated in other studies which detected PBDE in various environmental matrices (Katima *et al*., 2017, Talsness 2008). There is a possiblity that higher molecular weight BDEs debrominates to lower molecular weight BDEs as stated by Li *et a*l., (2014). We found deca-BDE (BDE-209), a high molecular weight BDEs having the highest concentrations at all sites. Therefore deca-BDE represents important reservoir lower-PBDE congeners. Generally, there were positive correlations between all the PBDE congeners. There were also positive correlations between all the PBDEs and the TOC in top soil. Correlation of TOC with PBDE suggests that PBDE binds to environmental matrix rich in organic carbon. As PBDEs bind strongly to soil particles, they may remain in soil for several years or even decades. TOC influences the distribution of PBDE in the soil and dust to some extent.

5.4.2 Implications of High PBDE Concentrations on Health and Environment

As PBDEs do not naturally occur in the environment, there is no doubt that e-waste recycling is a major source of PBDE pollution in Nigeria. When released, they bind strongly (especially congeners with higher content of bromine bind more strongly) to soil, sediment particles, and sewage sludge, in turn making them less mobile in the environment. Therefore, they bioaccumulate and biomagnify in aquatic organisms, fish, and plants, and are eventually transferred up the food chain, ultimately to humans (Bocio *et al*., 2003). Moderate to high PBDE congeners are found in air samples closer to the source of pollution, while PBDE congeners with less bromine atoms travel greater distances from their same source (Strandberg, Dodder, Basu, & Hites, 2001), meaning that people living far away from the source of release may also be at risk of exposure to PBDE. It is assumed that the higher PBDEs may degrade to lower PBDE congeners like tetra-, penta-, and hexa-BDEs in the environment, and that the PBDE with lesser bromine atoms are more persistent in the atmosphere (O'Driscoll *et al*., 2016).

The $\sum_{17}$PBDE concentrations found in soils and various dust samples exceeded the ATSDR oral MRL (Minimal Risk Levels) of 0.00006 mg/kg/day for lower-brominated PBDEs based on a LOAEL (lowest-observed-adverse-effect level) for endocrine effects in rats. Our values also exceeded The EPA's reference doses (RfDs) for penta, octa-, and decaBDEs are $2x10^{-3}$, $3x10^{-3}$, and $7x10^{-3}$ mg/kg/day, respectively (Hana *et al*., 2017), suggesting that PBDE could adversely affect animals and other sensitive species in the environment, and consequently humans in and around the study areas. Humans can be exposed to PBDEs and metals though inhalation, dermal absorption, and consumption of contaminated foods such as fish, meat, and dairy products (Siddiqi *et al*., 2003, Fujimori *et al*. 2012). This is a considerable environmental concern and most likely a health concern. We recommend further toxicological studies on the e-waste workers. It is hoped that the results of this study are a wake-up call on the need for more effective strategies on enforcement of e-waste regulations in Nigeria. We recommend that the enforcement would be effective if the regulations are made through the lens of the informal sector and enforcement agencies collaborates with the informal sector so as not to impade the workers' livelihood. The findings in this study is representative of what might be going on in other places unsafe e-waste recycling is practice, therefore solutions proferred for Nigeria is applicable to other places.

5.5 Conclusion

Our study showed that PBDE concentrations at the e-waste recycling sites were elevated compared to those detected at the control sites by 100s to 1000s times, with BDE-209 being the most abundant in all the samples and at all the sites. There was a significant difference in concentrations of PBDEs between the e-waste activities and the control sites, and within the e-waste sites for most of the PBDE congeners. This proves that the type of activities at the sites influences the level of PBDEs, with burning activities having the most effect. This study demonstrates that crude recycling of e-waste contributes significantly to emissions of organic pollutants in the environment. Comparing our results with past studies in Guiyu, China, the PBDE concentrations are high, suggesting that the situation calls for urgent action. There is an urgent need for action to stop open burning of e-waste and to reverse or stop the environmental deterioratation as a result of informal *e*-waste recycling.

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Chapter 6

Health Risk of Polybrominated Diphenyl Ethers and Metals at Informal Electronic Waste Recycling sites

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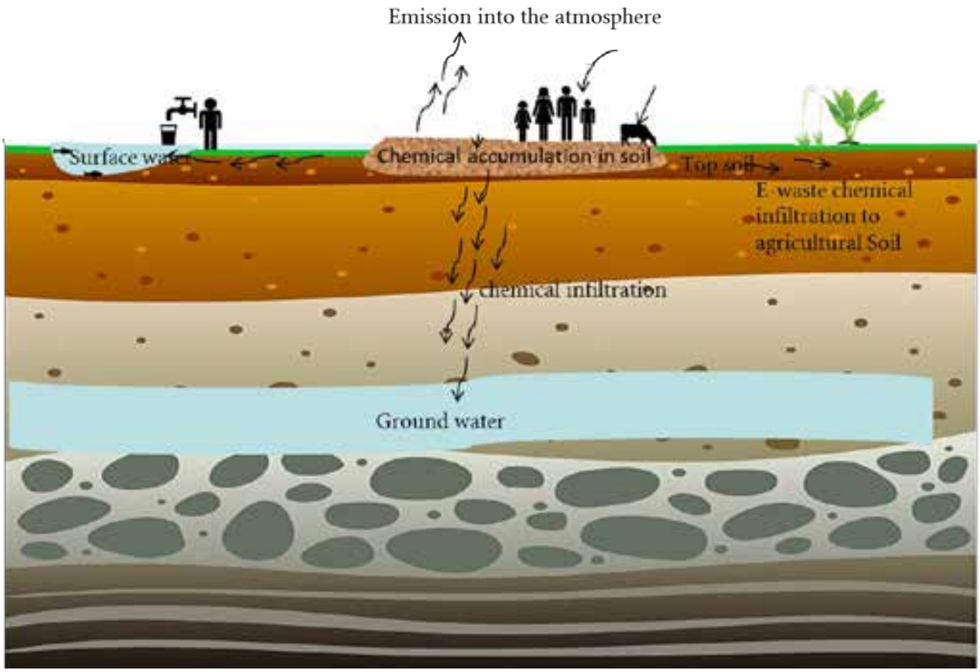
(Submitted)

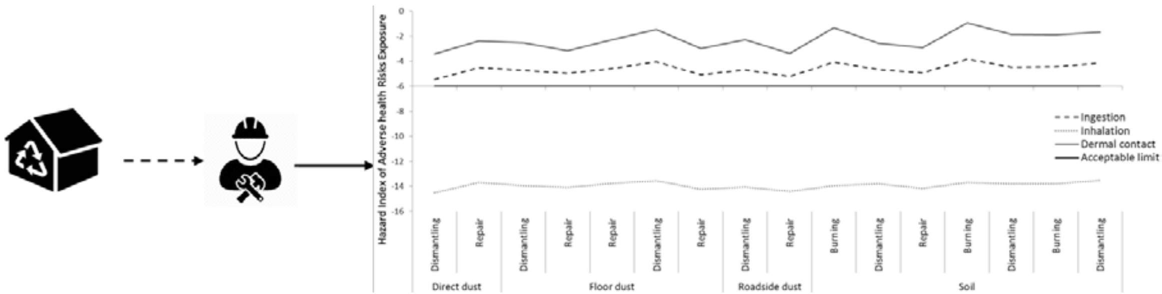


Contamination Routes due to Informal E-waste Recycling at one Site

Abstract

Concerns about the negative consequences of informal e-waste recycling in developing countries are increasing. Insight into the pollution level and its associated health risks to humans through scientific assessments, offers a crucial basis for devising appropriate e-waste recycling management strategies aimed at reducing adverse health effects of informal e-waste recycling. To understand the health impacts of various informal e-waste recycling activities in Nigeria, we calculated the average daily dose for 17 Polybrominated Diphenyl Ethers (PBDEs) congeners and 22 metals in top soils and dust samples, through 3 different exposure routes:- ingestion, inhalation, and dermal contact.

The estimates of non-carcinogenic and cancer risks of both PBDEs and metals exceeded the safe threshold limit by several folds. The major route of exposure was dermal contact followed by ingestion, while inhalation was found to be the least important exposure route. The high health risk revealed in this study should be considered as a wake-up call on the need for appropriate safety measures to be enforced in the e-waste recycling sector in Nigeria.



Graphical Abstract

6.1 Introduction

Information Communication Technology (ICT) has revolutionized our everyday life, consequently causing an increasing demand for ICT. This growing importance of ICT coupled with rising obsolescence due to rapid technological advancements and decreasing electrical electronic equipment (EEE) lifetime has led to a rapid increase in the volume of waste electrical electronic equipment (WEEE also known as *e*-waste) generated around the globe. E-waste consists of electrical and electronic devices including all separate components (such as wires, cables, batteries, circuit boards) which are at the end of their useful life (Baldé *et al*., 2015). The global estimate of e-waste generated in 2014 was 41.8 million metric tons, which increased to 44.7 million metric tons in 2016, and 52 million metric tons are expected to be generated by 2021 (Baldé *et al*., 2017). Of the quantity generated, only about 20% of e-waste generated is properly collected and recycled (Baldé *et al.,* 2017). About 80% of the e-waste generated globally is recycled in informal settings in developing countries such as Nigeria, Ghana, Brazil, Mexico, China, India, Vietnam, and the Philippines (Perkins *et al*., 2014, Awasthi *et al.,* 2016). E-waste is one of the most complex waste streams because of the wide variety of components, compositions, and rapidly changing product designs. It is also one of the fastest growing municipal waste streams in the world.

Electronic and electrical equipment contains over 1000 different substances, some of which are compounds of potential concern (COPC) which include metals, products of incomplete combustion (PICs), and/or reformation products. PICs include any organic compound emitted during incomplete combustion, whereas reformation products are organic compounds that are formed immediately after combustion, due to interaction of specific constituents in the combustion gasses during the combustion process. Some of the organic compounds are persistent organic pollutants (POPs) such as brominated flame retardants (BFRs) like Polybrominated Diphenyl Ethers (PBDEs), non-dioxin like Polychlorinated Biphenyls (PCB), Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorinated Dibenzo-p-dioxins and Furans, or PCDD/Fs. These POPs along with other organic compounds may pose significant implications for human health and environmental safety (UNEP-DTIE, 2007, Brigden *et al*., 2008; Asante *et al.,* 2012).

In this study, we considered PBDEs as a proxy for the cocktail of POPs emitted at informal e-waste recycling sites. POPs like PBDEs are toxic, highly persistent in the environment, bioaccumulative in food chains, and they have a high potential for long-range environmental transport. In addition,

metals from e-waste are non-biodegradable, they persist in the environment and can disturb the ecological balance of the aquatic and the terrestrial environment, as well as affect human health.
These chemicals have been detected in humans and in increasing concentrations in various environmental matrixes, including air, water, soil, sediment, animals and foods in all regions of the world. Evidence of effects of exposure to informal e-waste recycling activities also includes injuries (Ohajinwa *et al*., 2017b), infection of wounds, skin and eye injuries and irritations, respiratory problems, and noise among others (Kristen, 2013; Chen *et al*., 2011). There is also evidence on harmful effects of long-term exposure of humans and wildlife, which include effects on fetal/child development, impacts on thyroid and neurologic functions, immunotoxicity, reproductive toxicity, and endocrine disruption with endpoints related to induction of cancer: See table 1 for more information on health effects due to exposure to organic and metal contaminants.

Table 6.1: Some evidences of Health Effects due to Long-term Exposure to Persistent Organic Contaminants.

Chemical	**Effects**	**Reference**
PCDD/Fs	Thyroid function	Zhang *et al*. 2010
PBDEs	Thyroid function, Reproductive health, endocrine disruption	Zhang *et al*. 2010, Yuan *et al*. 2008, Wu *et al*. 2010, Wang *et al*. 2010,
PCBs	Reproductive health, thyroid function	Zhang *et al*. 2010, Wu *et al.* 2010
PATHs, PFOA	Reproductive health	Wu *et al*. 2011,Wu *et al*. 2012
Cr, Mn, Ni	Lung function	Zheng *et al*. 2013
Pb, Cr, Cd, Ni	Reproductive health	Guo et al. 2010, Li *et al*. 2008a, Xu *et al*. 2012
Mn, Ni, Pb	growth	Huo *et al*. 2007, Zheng *et al*. 2013
Pb	Mental health outcomes	Liu *et al.* 2011, Li *et al*. 2008b
As, Cd, Ni, Cr, Hg, Cu	Cancer, oxidative stress, DNA damage	IARC, 2012, Järup 2003, European Commission 2003

Due to a lack of infrastructure for environmentally sound management of e-waste, lax environmental laws/regulations, and weak enforcement of existing laws/regulations (NESREA 2013, FRN 2011, SAICM 2009, UNEP 1991, WHO 1989), e-wastes are often informally recycled using crude methods such as manual dismantling, smelting, and open burning. Informal e-waste recycling is unsafe, unregulated, unorganised and often overlooked (Brigden *et al*., 2008, Asante *et al*., 2012, Ohajinwa *et al*., 2017a). This leads to incomplete combustion, consequently releasing a mixture of hazardous chemicals, including PBDEs and metals, which in turn cause environmental contamination and health problems.

Disturbingly high concentrations of metals and PBDEs have been found at and around informal e-waste recycling sites, of which Nigeria is inclusive (Ohajinwa *et al.,* 2018). Large quantities of e-waste are informally recycled in Nigeria using various recycling activities such as repair, dismantling, and burning. Each of these activities may pose a potential significant source of human exposure to pollutants (toxic metals and organic pollutants) e.g. through direct inhalation, ingestion, dermal contact or via consumption of food and water. So far, to our knowledge, no study has estimated the associated health risks. Therefore, there is a need to estimate the health risks associated with exposure to e-waste chemicals such as metals and PBDEs. The most evident health-related issues are associated with direct occupational exposure. In addition to these apparent health issues, which are sometimes short term, there might be some unforeseen threatening health issues in the long run or even after the person has stopped working at e-waste sites. To provide an understanding of the health risks to which e-waste workers at the informal e-waste recycling sites in Nigeria are exposed to, we estimated the health risks of exposure to metals and PBDEs pollution as present in top soils (0-10cm) and various dust samples (floor dust, floor dust, and direct dust from electronics). We did this by calculating average daily doses for workers exposed via inhalation, dermal contact and oral ingestion.

Specifically, we aimed to investigate the potential of e-waste workers for (1) non-cancer risks and (2) cancer risk as a result of exposure to metals and PBDEs. In this study, we consider exposure to PBDEs and metals as a proxy for organic and inorganic chemicals respectively. E-waste workers are inadvertently exposed to both classes of chemicals at various informal e-waste recycling sites. In this paper we evaluate 17 PBDE congeners BDE-17, BDE-28, BDE-71, BDE-47, BDE-66, BDE-100, BDE-99, BDE-85, BDE-154, BDE-138, BDE-183, BDE-190, BDE-208, BDE-206, BDE-209, as well as 22 metals Ag, As, Ba, Cd,Cr, Co, Cu, Fe, Ga, Ge, Hg, Mn,Ni, Pb, Se, Sn, Sb, Te, Ti, Ta, V, and Zn, at the various sites.

6.2 Methods

6.2.1 Study Locations and Designs

The methods employed in this study have been well detailed in our previous studies (Ohajinwa *et al*., 2017a, Ohajinwa *et al.,* 2017b, Ohajinwa *et al.,* 2018). In brief, this study was conducted in three study locations/cities are Ibadan, Lagos, and Aba. The three study locations are some of the large cities in Nigeria where e-waste is recycled (Ogungbuyi *et al*., 2012). In each study location, two e-waste recycling areas were selected. In Lagos, the selected sites were Computer village, Ikeja (6.593^{o}N, 3.342^{o}E) and Alaba international market Ojor (6.462^{o}N, 3.191^{o}E). In Ibadan, the selected sites were Ogunpa (7.383^{o}N, 3.887^{o}E) and Queens Cinema areas (7.392^{o}N, 3.883^{o}E). In Aba, the shopping centre (5.105^{o}N, 7.369^{o}E) and Port-Harcourt Road/Cementary (5.104^{o}N, 7.362^{o}E) and Jubilee road/St Michael's Road (5.122^{o}N, 7.379^{o}E) were selected (figure 6.1).

A comparative cross-sectional study design was adopted to gain an understanding on the pollution levels at the e-waste recycling sites in the three study locations in Nigeria. In each study location, a multi-stage random systematic sampling technique was used to ensure representative inclusion of various e-waste recycling activities (burning, dismantling, and repair) in the selected e-waste recycling areas. Soil and dust samples were collected from the selected sites depending on the feasibility of collecting such samples. For metal analysis, a total of 62 samples consisting of 23 top soil (0-10 cm depth), 31 floor dust, 3 roadside dust, and 5 direct dust samples collected from the inside and outside of electronic devices were analysed. For the PBDE analysis, a total of 56 samples consisting of 16 top soils (0-10cm), 29 floor dust, 5 roadside dust, and 6 direct dust samples collected from the inside and outside of electronic devices were analysed, see supplementary figure 6.1a and 6.1b.

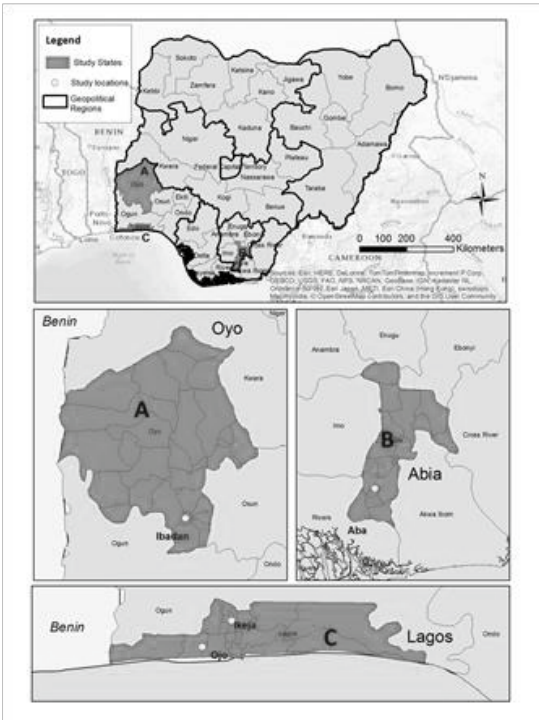


Figure 6.1. Map of Nigeria showing the Study Locations

6.2.2 Description of Recycling Activities and likely Exposure Pathways

The recycling activities include storage, washing, cleaning, dismantling, and metal recovery through stripping of wires or open burning. Most *e*-waste recycling activities (especially at dismantling and burning sites) are carried out outdoors, which involve manually dismantling (disassembling) using hammer, machetes or any tool that can help separate the parts. Open burning leads to incomplete combustion and processed materials from the various e-waste activities are dumped outside on bare ground (no vegetative cover on the ground). Most repair activities, which involve soldering of various parts, take place indoors but also sometimes outdoors, depending on the settings of the work environment and the weather condition. These activities release large quantities of hazardous substances without any emission control.

The workers work without caution to protect their health (no use of personal protective equipment (PPE)) or the environment. The majority (82%) of the workers work without use of any PPE such as gloves, nose mask, also most of them work in shorts, short-sleeved shirts, and slippers (Ohajinwa *et al.,* 2017a,b. This means that they have multiple routes of exposure (directly and indirectly) to the e-waste chemicals. The exposure routes are via ingestion, inhalation, or dermal contact. Informal e-waste recycling happens mostly in urban slums, usually with no official governance, regulations, and people work mainly for economic benefits. Within the e-waste recycling vicinities, there are other (non e-waste recycling) informal businesses. In some locations there are water bodies less than 2 km away from the burning sites. In addition, most residences use boreholes (ground water) and deep wells as a source of water as confirmed by Healya *et al*., 2017. Historically, it seems that e-waste recycling activities were the first activities that release hazardous substances at least at the levels observed. Due to stricter enforcement of the e-waste regulations by the National Environmental Standards and Regulations Enforcement Agency (NESREA), the e-waste dumpsites/burning sites have been moved more than once at Alaba, Lagos. After a while the new sites were crowded with both old and new in-coming workers (usually migrants in search of greener pasture in the cities). As the migrants settle around the dumpsites, the sites finally turn into a small temporary unplanned residential community. One major concern is that current e-waste sites could be used for other activities in the future, which means that the impact of the emissions from e-waste recycling could go beyond the e-waste workers. We recognize that children around the e-waste recycling sites may be exposed to e-waste mixture chemicals, but in this study we focus on e-waste workers' exposure to metals and PBDEs that are likely to be emitted during e-waste recycling.

6.2.3 Health Risk Assessment

Considering the high concentrations of metals and PBDEs at the e-waste sites and the poor work practices, we estimated the potential health risks exposure of e-waste workers via various routes at the various sites. Risk assessment is the process of quantitatively determining the likelihood of adverse health effects resulting from exposure to contaminants over a specified time period. The risk estimation as based on the magnitude, frequency, and duration of human exposure to chemicals

(PBDEs and metals in this study) in the environment is commonly expressed as the average daily dose (ADD). Information on the socio-demographic (age, weight, height) and occupational characteristics were obtained from the e-waste workers, which were used for the health risk estimates. The health risk or hazard of each of the metals, each of the PBDE congeners, and ∑PBDEs is expressed in terms of either a carcinogenic risks or a non-carcinogenic health hazards. Exposure to PBDEs and metals can occur via three main pathways: (a) direct inhalation of vapour or of atmospheric particulates through mouth and nose; (b) incidental ingestion of dust and top soils due to their deposition on food or drinks or via hand-to-mouth activity, and (c) dermal absorption of substances present in particles adhering to exposed skin (Ferreira-Baptista and Miguel, 2005). The models used in this study to calculate the exposure of humans to metals and PBDEs in dust and soil is based on the models developed by the Environmental Protection Agency of the United States (USEPA 2002, USEPA 2001) and the exposure Factors Handbook (USEPA, 1997).

The average daily dose (ADD) (mg/kg/day) of a pollutant in soil and dust taken up via ingestion, dermal contact, and inhalation as exposure pathways can be estimated using Equations (1-3), given below. $ADD_{ingestion}$, $ADD_{inhalation}$, and ADD_{dermal} are the daily amounts of PBDEs and metals taken up through ingestion, inhalation and dermal contact (mg/kg/day) respectively. Median concentrations of the pollutants were used in these calculations. The values and factors used for the estimations are from the standards set by USEPA and actual data, see table 6.2 also for meanings of the abbreviations.

$$ADD_{ingestion} = C \times \frac{R_{ing} \times EF \times ED}{BW \times AT} \times CF \qquad \text{Equation (1)}$$

$$ADD_{dermal} = C \times \frac{SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times CF \qquad \text{Equation (2)}$$

$$ADD_{inhalation} = C_{dust} \times \frac{R_{inh} \times ET \times EF \times ED}{PEF \times BW \times AT} \times CF \qquad \text{Equation (3)}$$

Table 6.2: Exposure Parameters for Adults (E-waste workers) with Associated References.

Abbreviations	Exposure factors	Exposure values	References
C (mg/g)	Median Concentration of the PBDE or metals	Shown in supplementary tables 6.1-6.6	This study
R_{ing} (mg/day)	Ingestion rate	30 mg/day	USEPA 2011
R_{inh} (m^3/day)	inhalation rate	20 m^3/day	USEPA, 2001
EF (days/year)	Exposure frequency	313 days/year	This study
Work days	Average work days	6 days/week	This study
ED (years)	Exposure duration	24 years	USEPA, 2001
ET (hours/day)	Exposure time in hours/day at work	9 hours/day	This study
BW (kg)	Average body weight	67 kg	This study
AT (days)	Average time (ED X 365 days) for non-carcinogens)	24 X 365 days	USEPA, 2001
	Average time (70 X 365 days) for carcinogens	70 X 365 days	USEPA, 2001
Age	Median age of the workers	29 years	This study
SA (cm^2)	Skin surface area	5700 cm^2 (most of them do not use any PPE)	USEPA, 2004
AF (unitless)	Skin adherence factor	0.2 mg/cm^2.day	USEPA, 2001
ABS (unitless)	Dermal absorption factor	0.1 (for semi-volatile compounds)	USEPA, 2001
PEF (m^3/kg)	Particle emission factor	1.36 X 10^9 m^3/kg	USEPA, 2001
CF	Conversion factor	10^{-6}	USEPA, 2001
RfD_i (mg/kg/day)	reference dose via ingestion, inhalation, and dermal contact	available for four PBDE congeners and 19 metals	USEPA 2017
RfC (mg/m^3)	Reference concentration	--	USEPA 2017
IUR	Inhalation Unit Risk	--	USEPA 2017
ADD (mg/kg/day)	average daily dose	Calculated and shown in supplementary tables 6.7-6.12	This study
HQ (unitless)	Hazard quotient	--	
HI	Hazard index	--	
SF	Slope factor	--	USEPA 2017

Based on the ADDs, and the toxicity risk indices, the health risks for no-cancer hazards and cancer risks) of the PBDEs and metals were estimated using equation 4-5. The Hazard Quotient (HQ) is used to calculate the non-carcinogenic risks based on reference daily dose (RfD) (USEPA, 2005), (Lim, Lee, Chon, & Sager, 2008). The RfD is an estimate of the allowable daily exposure to the human population (Leung *et al*., 2008). Values for RfD were available only for four PBDEs congeners (BDE-47, BDE-99, BDE-153, and BDE-209), and for 19 metals: Ag, As, Ba, Cd, Cr, Co, Cu, Fe, Hg, Mn, Ni, Pb, Se, Sn, Sb, Ti, Ta, V, and Zn from USEPA 2011 and USEPA 2017. A HQ value below one indicates that there is an acceptable level of risk (indicating no probability of any adverse effect), while HQ values exceeding one are indicative of unacceptable risks (indicating probability of an adverse health effect) and HQ values exceeding one are assumed to be of concern (USEPA, 2011). The HQ for each of the pollutants (PBDEs and metals) was calculated for ingestion, dermal contact, and inhalation pathways. The health risk for carcinogen risk characterization is based on the slope factor (SF) and the Inhalation Unit Risk (IUR). The slope factor (mg kg-1 day-1) is used in risk assessment to estimate the lifetime probability of an individual developing cancer as a result of exposure to a particular carcinogen. The carcinogenic risk is the probability of an individual developing any type of cancer from lifetime exposure to carcinogenic chemicals. A risk above 1×10^{-4} is generally considered to be unacceptable, a risk below 1×10^{-6} is considered not to trigger any health effect, while risks calculated to be in between 1×10^{-4} and 1×10^{-6} are within the acceptable limits. This means that a risk at 1×10^{-6} is interpreted as indicating that an individual has a one in 1,000,000 chance of developing cancer from the exposure evaluated (Adamu *et al*., 2015; Du *et al*., 2013; Olujimi *et al*., 2015).

Oral Hazard Quotient (HQ_{ing}) = ADD/RfD Equation (4a)

Inhalation Hazard Quotient (HQ_{inh}) = ADD/RfC Equation (4b)

Dermal Hazard Quotient (HQ_{der}) = ADD/(RfD X GIABS) Equation (4c)

Carcinogenic $risk_{ing}$ = ADD_{ing} X SF Equation (5a)

Carcinogenic $risk_{inh}$ = ADD_{inh} X IUR Equation (5b)

Carcinogenic $risk_{der}$ = ADD_{der} X (SF X GIABS) Equation (5c)

GIABS is the gastrointestinal absorption factor was assumed to be equal to one (assuming the total absorption of contaminants for all congeners) (USEPA 2017).

In addition, the Hazard Index (HI) is used to assess the potential of exposure to multiple chemicals or multiple exposure routes at the sites to cause non-carcinogenic effects through different pathways. The hazard index is equal to the sum of the HQ values for the individual chemicals. Since the workers are exposed to multiple substances (both metals and PBDEs) within individual exposure pathways, we estimated the total non-cancer hazard by summing up the HIs of metals and PBDEs for each of the exposure routes. We assume there are no interactions between PBDEs and metals.

6.3 Results

6.3.1 Descriptive Statistics of the PBDE and Metals

In the Supplementary tables S6.1 – S6.6, a summary of the medians of the various PBDE and metal concentrations in soil and in dust samples at the various e-waste recycling sites is shown for each of the three study locations. The general pattern of the PBDEs and metal distribution in top soil and dust samples from the sites showed concentrations in this increasing order: control sites < repair sites < dismantling sites < burning sites. The concentrations of most of the PBDE and metals congeners at the e-waste sites in the three locations exceeded the concentrations at the corresponding control sites.

6.3.2 Human Health Risk Assessment

6.3.2.1 Quantitative Estimation of Non-Carcinogenic Effects

The HI values for dermal exposure to soil and dust were greater than one at all e-waste recycling sites (burning, dismantling, and repair sites), particularly for metals. This indicates that the concentrations at those sites exceeded the threshold (safe) limit and the workers are at risk of contracting non-cancer health effects via dermal exposure, followed by ingestion of soil and dusts at the sites. In contrast, the non-carcinogenic risks via inhalation were negligible. Dermal contact was shown to be the main route of exposure to both metals and PBDEs and consequently poses a higher risk. Generally for the PBDEs, BDE-209 contributed most to the health risk, followed by BDE-99 in Lagos and Ibadan, while in Aba BDE-99 contributed most followed by BDE-153. Figures 6.2 and 6.3 present the hazard index (HI) of top soils and dust for non-cancer risks via all exposure pathways at the e-waste sites for the three locations for PBDEs and metals, respectively. See supplementary tables 6.13-6.15 and 6.17-6.19 for more details.

Combining the HIs for non-cancer risks of metals and PBDEs also revealed that the total HI exceeded the acceptable (safe) limit for non-cancer hazards via dermal exposure at all sites in all locations, and also via ingestion of direct dust at repair sites and ingestion of top soils at burning sits in Lagos (figure 6.4, and supplementary table 6.17). We also considered the cumulative non-cancer effects by summing the risks from all exposure routes. The cumulative non-cancer effects exceeded the accepatable limit at all sites in all locations, see figure 6.5.

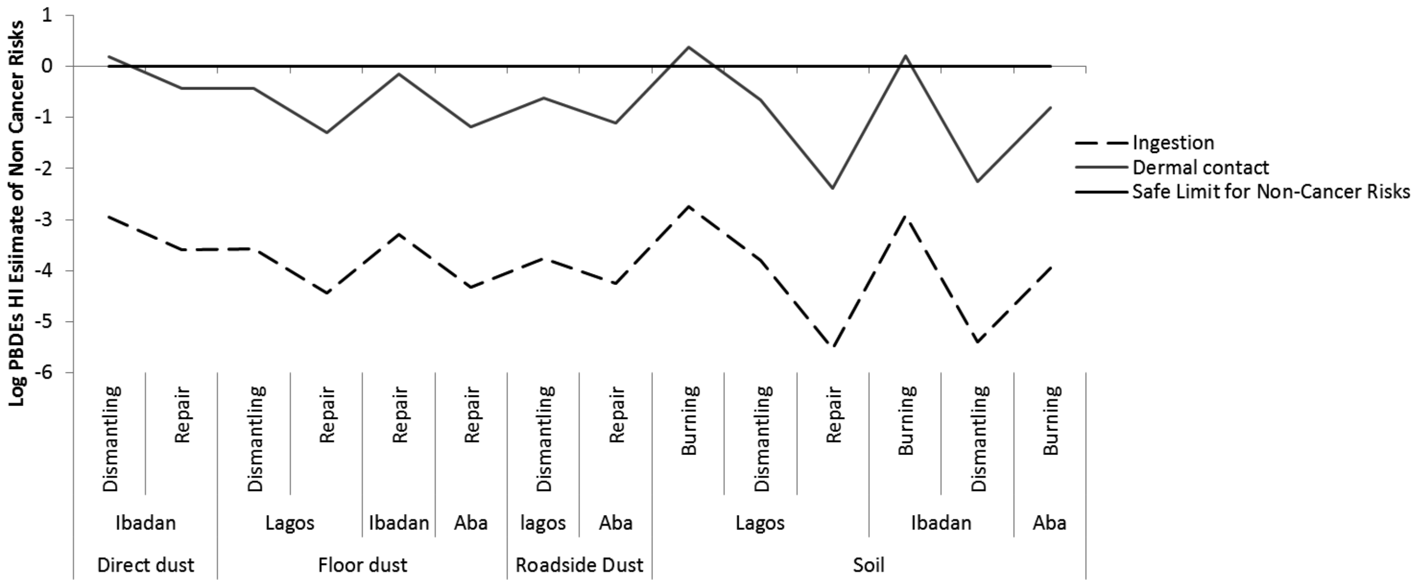


Figure 6.2. Hazard index (HI) for Non-Cancer Risk via Ingestion and Dermal Contact of PBDEs in Soil and Dust at various E-waste sites in Three locations.

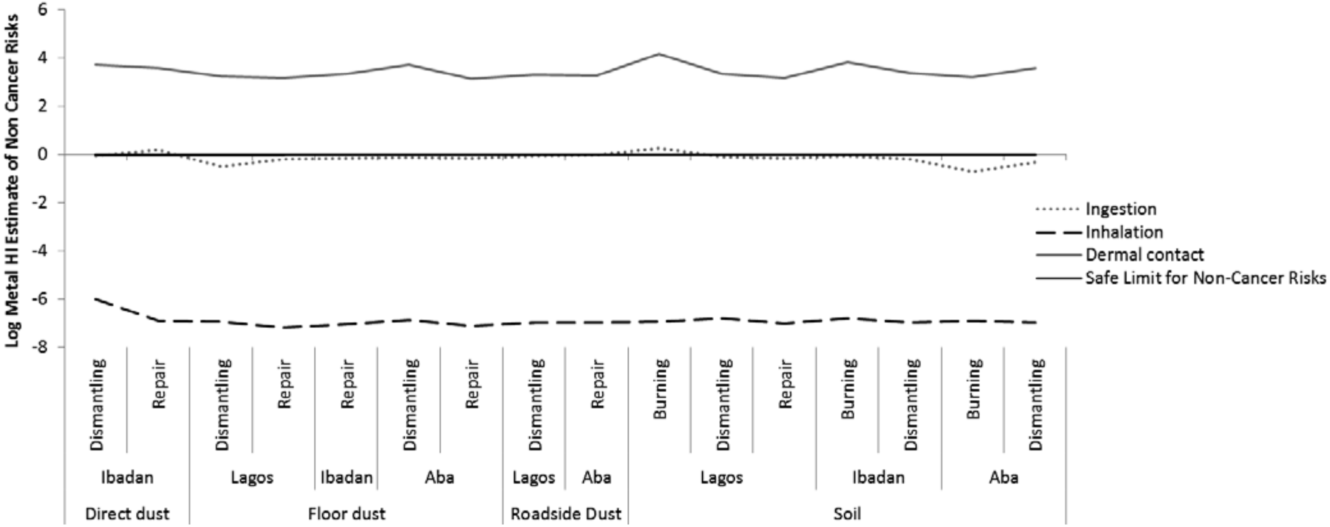


Figure 6.3. Hazard index (HI) for Non-Cancer Risk of Metal Exposure via Ingestion, Inhalation, and Dermal Contact of Soil and Dust at various E-waste sites in the three locations. It shows that e-waste workers are prone to non-cancer risks via dermal contact with metals in soils and dust, also via ngestion of top soils at burning sites in Lagos.

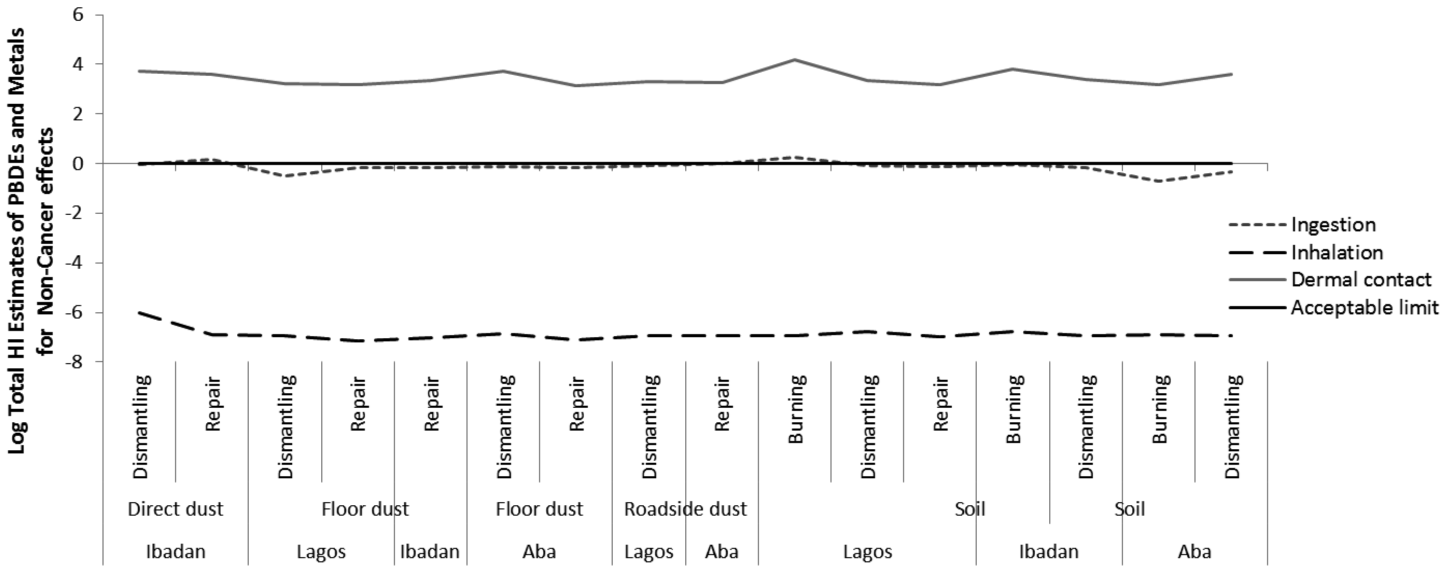


Figure 6.4. Total Hazard index (HI) for Non-Cancer Risk via each Exposure Route of Metal and PBDEs in Soil and Dust at various E-waste sites in the three Locations.

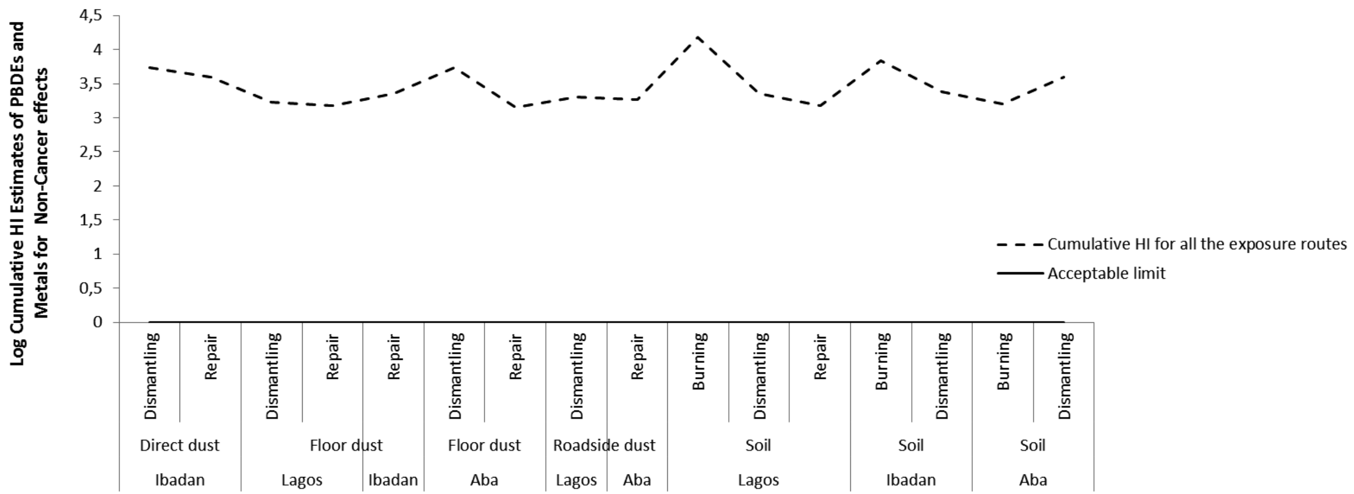


Figure 6.5. Cumulative Hazard index (HI) of all Exposure Routes for Non-Cancer Risk of Metal and PBDEs in Soil and Dust at various E-waste Sites in the Three Locations

6.3.2.2 Quantitative Estimation of Risk of Contracting Cancers

The cancer risk for BDE-209 via ingestion is within the range of 2.3 X 10^{-10} to 8.5 X 10^{-06}, and for dermal uptake is between 3.2 X 10^{-07} to 1.2 X 10^{-2}. This indicates that the risks of contracting cancer via ingestion and dermal contact are above the safe limit of 1 X 10^{-6}, showing that workers at the burning sites are prone to cancer risks via dermal contact of PBDEs; see Figure 6.6 and supplementary tables 6.21-6.23 for more details. These findings indicate that exposure of e-waste workers to PBDEs is potentially harmful to their health.

Only six metals with toxicity values (Cr, Co, Ni, As, Cd, Pb) were used to estimate the potential cancer risks via ingestion, inhalation, and dermal contact. The HI for cancer risk through metals via ingestion ranged from 3.4 X 10^{-06}, to 1.5 X 10^{-04}, via inhalation it ranged from 3.3 X 10^{-15} to 2.90 X 10^{-14}, and via dermal contact it ranged from 3.9 X 10^{-04} to 1.2 X 10^{-01}, see figure 6.7 the results for each of the locations, and the supplementary tables 6.24-6.26 for more details. These results show that exposure via inhalation induces risks that are below the safe limit, while exposure via ingestion and dermal contact induces risks that exceeded the safe limits at all sites in all locations. These findings indicate that the workers are at most risk of adverse non-cancer health effects via dermal contact, followed by ingestion, while exposure via inhalation induces negligible risks. The burning sites seem to be the most unsafe sites followed by the dismantling and repair sites. These findings indicate that exposure of e-waste workers to metals is harmful to their health.

Since the workers are exposed to multiple substances (both metals and PBDEs) within individual exposure pathway, we estimated the total cancer risk by summing up the HIs of metals and PBDEs for each of the exposure routes. The total HI shows that the exposure via ingestion and dermal contact of metals and PBDEs exceeded the acceptable (safe) limit for cancer risks at all sites in all locations (figure 6.8, and supplementary table 6.27). We also considered it appropriate to sum risks from multiple exposure routes (i.e the cumulative risk of exposure). Obviously, the cumulative cancer risk also exceeded the acceptable (safe) limit at all sites in all locations, see figure 6.9.

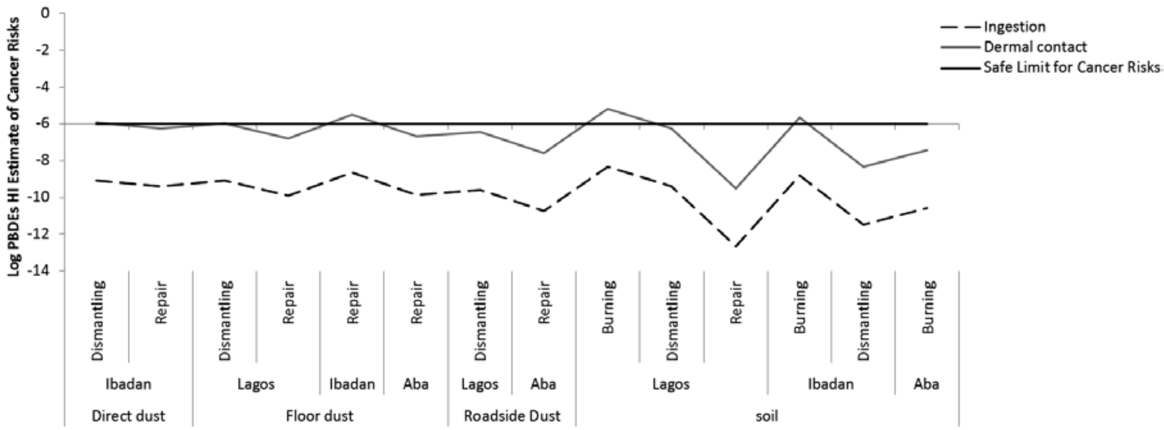


Figure 6.6. Hazard index (HI) for Cancer Risk via Ingestion and Dermal Contact of PBDEs in Soil and in Dust at various E-waste Sites in the Three Locations.

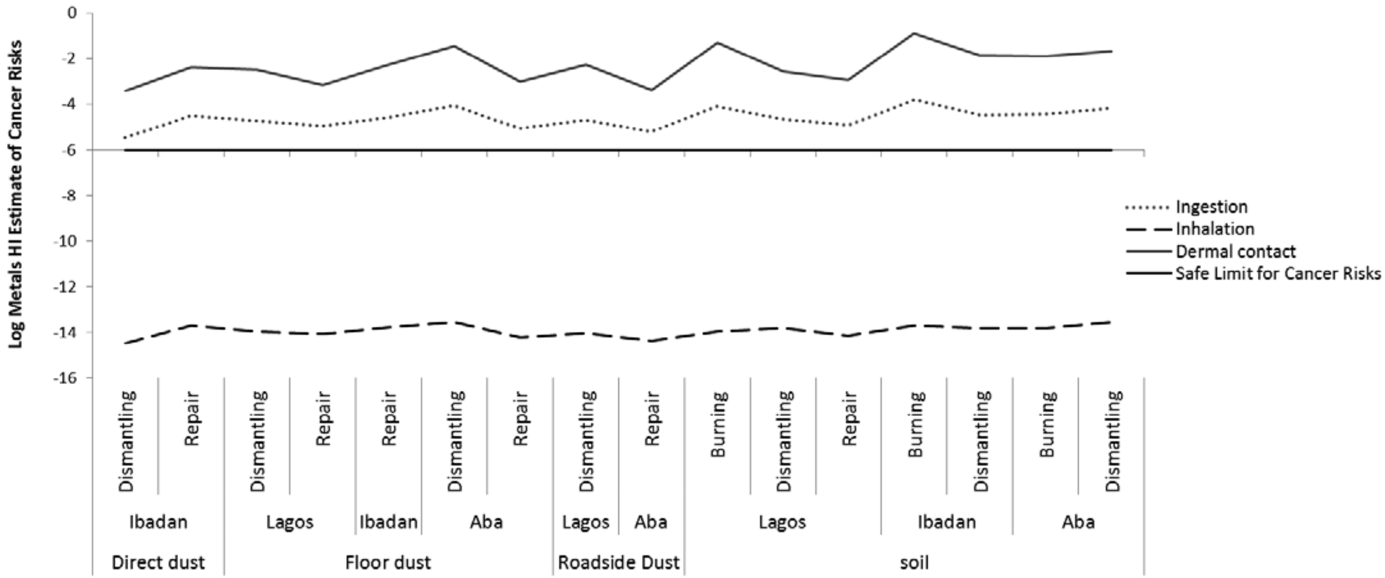


Figure 6.7. Hazard index (HI) for Cancer Risk via Ingestion and Dermal Contact of Metals in Soil and Dust at various E-waste Sites in the Three Locations.

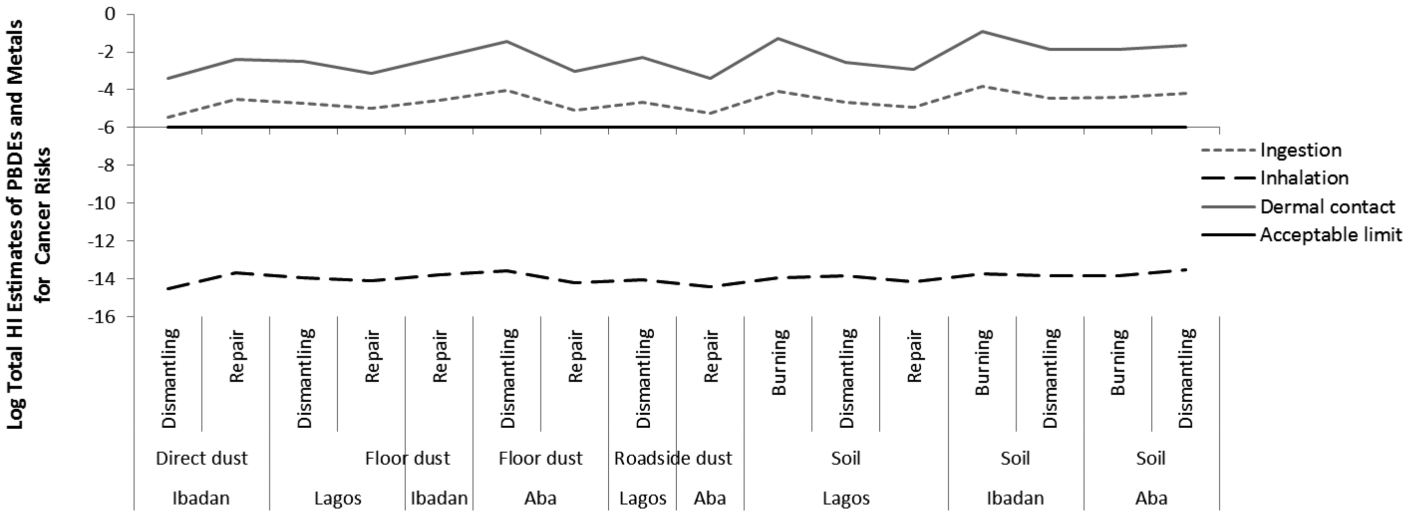


Figure 6.8. Total Hazard index (HI) for Cancer Risk via each Exposure Route of Metal and PBDEs in Soil and Dust at various E-waste sites in the three locations.

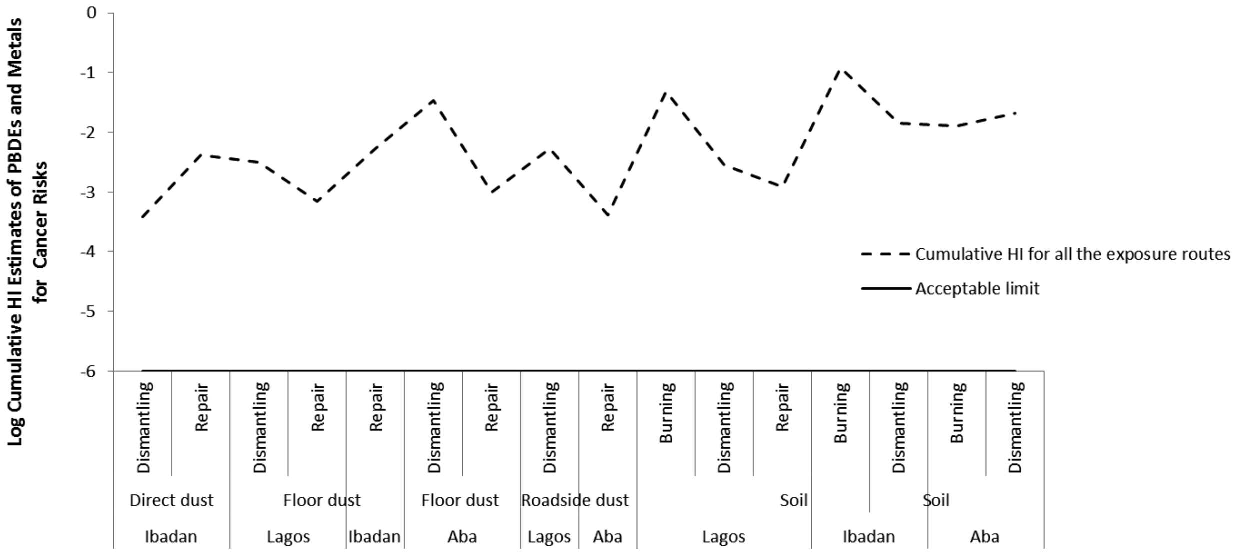


Figure 6.9. Cumulative Hazard index (HI) of all Exposure Routes for Non-Cancer Risk of Metal and PBDEs in Soil and Dust at various E-waste Sites in the Three Locations.

6.4. Discussion

As far as we are aware, this is one of the few studies that estimated the cancer risks and non-cancer hazards of exposure to PBDEs and metals in soil and dust samples from different informal e-waste activity sites (burning, dismantling, and repair sites). The strenghth of this study is that, we considered three exposure pathways, different e-waste recycling activities, various environmental samples (top soils and dusts) from different types of e-waste recycling, and compared exposure in three different cities in two different geopolitical zones in Nigeria. We estimated non-cancer effects, cancer risks, and the assessed the cumulative effect of exposure to both PBDEs and metals via all exposure routes. We also used some primary data on exposure parameters obtained from the respondents for the risk estimation, instead of using US EPA exposure parameters which are commonly used in other studies. In addition, we used epidemiological methods to select the right target groups and sites to ensure that the results obatained are a representative of the target groups and sites, and that the findings are applicable to similar situations anywhere in the world. Focusing on the three types of informal e-waste recycling provided a comprehensive insight on the health risks for different groups of e-waste workers. Workers are exposed to far more chemicals, therefore this study can be considered as being indicative of the risks due to both organic and inorganic chemicals.

The findings of this study as performed in Nigeria are likely to be representative for informal e-waste recycling in developing countries that lack the resources for safe e-waste recycling. Increasing amounts of electronic waste, unsafe recycling methods and disposal pose significant risks to the environment and human health, therefore hindering sustained health. Understanding the implications of scientific data related to informal e-waste recycling contributes towards the achievement of Sustainable Development Goals (SDGs) related to environmental protection (Goals 6, 11, 12, and 14), health (Goal 3), and Goal 8 that focuses on employment and economic growth (United Nations, 2015).

6.4.1 Health Risk Assessments

The median concentrations of the PBDEs and metals considered in this study showed overall an increasing trend of health risks at the sites as the intensity of the e-waste activities increased in this order: control sites < repair sites < dimantling sites < burning sites. This finding reveals that open burning of e-waste is the most risky e-waste processing/recycling activity. The risks associated with the high levels of e-waste chemicals and poor work practices call for concern.

The health risk assessment shows the impact of the different metals and PBDE congeners via viarious routes (ingestion, inhalation, and dermal contact). Overall, the non-cancer effects and cancer risks of exposure to PBDEs is in this order: dermal contact, followed by ingestion of soil and dust at all the sites (burning, dismantling and repair sites). The same pattern of exposure risks are revealed for metal exposure: dermal contact, followed by ingestion, while exposure via inhalation is negligble. This finding is consistent with a similar study on e-waste sites reported by Civan and Kara (2016).

6.4.1.1 Implications for Health Risks

The cumulative hazard index of PBDEs and metals via all exposure routes at all the e-waste sites exceeded the acceptable (safe) limits by several orders of magnitude. Considering the exposure via the different routes to both PBDEs and metals, the total risks calculated shows that exposure via dermal contact exceeds the acceptable limit for non-cancer effects in all locations at all sites with the burning sites having the highest risks. Similarly, total risks for ingestion and dermal contact exceeded the acceptable limits for cancer risks in all locations at all sites with the burning sites having the highest risks. For both non-cancer effects and cancer risks, dermal exposure is the main route of exposure. This stresses the need for use of personal protective equipment (PPE) especially, appropriate work cloths. In addition, the cumulative health risks via all routes of exposure (inhalation, ingestion, and dermal contact) exceeded the acceptable limits of both non-cancer effects and cancer risk at all e-waste sites and in all locations. This indicates that overall the e-waste workers are at the risk of adverse health effects. This further emphasises the need for use of PPE. Exposure of e-waste workers to PBDEs, metals and other hazardous substances is even worsened, because the majority (82%) of the e-waste workers do not use any PPE (Ohajinwa *et al*., 2017b), 88% unaware that e-waste contains hazardous chemicals, and 70% do not think that the chemicals in e-waste can pose any health risk (Ohajinwa *et al*., 2017a). Ohajinwa *et al*., (2017a) also reported a positive correlation between workers' knowledge and work practice. Therefore improving e-waste workers' knowledge on the health risks associated with their daily jobs may decrease risky practices.

It is also important to note that other non-e-waste workers, residents, and children around the e-waste sites are equally at risk of adverse health effects from informal e-waste recycling. The high metal and PBDE concentrations at the e-waste sites may also be an indirect source of pollution of surface and ground water, and air; and could consequently affect people farther away from the e-waste sites. It should therefore be explicitly noted that the actual health risks will be higher than the risks calculated in this study. This indicates an urgent need for more appropriate and effective policies, regulations and strategies for enforcement actions suitable for the informal sector.

It is crucial that e-waste workers are educated of the potential health risks peculiar to their jobs and the safety measures to be undertaken. We recommend that government and other formal institutions design effective occupational health and safety programmes for the informal e-waste workers. There is also need to enforce the policies and regulations. One effective way of enforcement, is for formal institutions to work with the informal e-waste associations to communicate the health risks peculiar to informal e-waste recycling and the safety measures to be undertaken. Enforcement agencies must not be seen to be at cross-purposes with the informal e-waste sector, as it frequently appears. We also recommend the ban of open burning of e-waste and other risky practices which will consequently affect those living far away from the recycling sites and might even effect the unborn generation. One way to ensure such a ban is to device appropriate alternative ways of e-waste recycling with caution to protect health and enviroenment, bridge the commucation gap between enforcement agencies and informal e-waste workers, and also for the informal e-waste recycling associations to be made accountable for safer practices.

We also recommend the use of hierarchical control method in the informal e-waste recycling sector. Such controls are simple steps that will help to minimise exposure and health risks associated with informal e-waste recycling, without impeding the workers' source of livelihood (Figure 6.10). This will not only protect the e-waste workers but also protect people around the e-waste recycing sites.

In our assessment, we assumed that there is no interactions of chemicals that increase toxic effects to humans. Moreover, it is known that the toxicity of the chemicals also depends on other parameters such as exposure time, dose, age, oxidation state, solubility, and properties of the environment among others (Egorova & Ananikov, 2017). To address these uncertainties, we recommend further studies on biomonitoring of the e-waste workers in the informal e-waste recycling. We recommend further toxicological studies to determine the cumulative toxicological effect associated with exposure to multiple chemicals through different exposure pathways, because the additive response method applied in this study might underestimate the potential for health effects. We also recognize that we did not identify all compounds present in the emissions at the e-waste recycling sites.

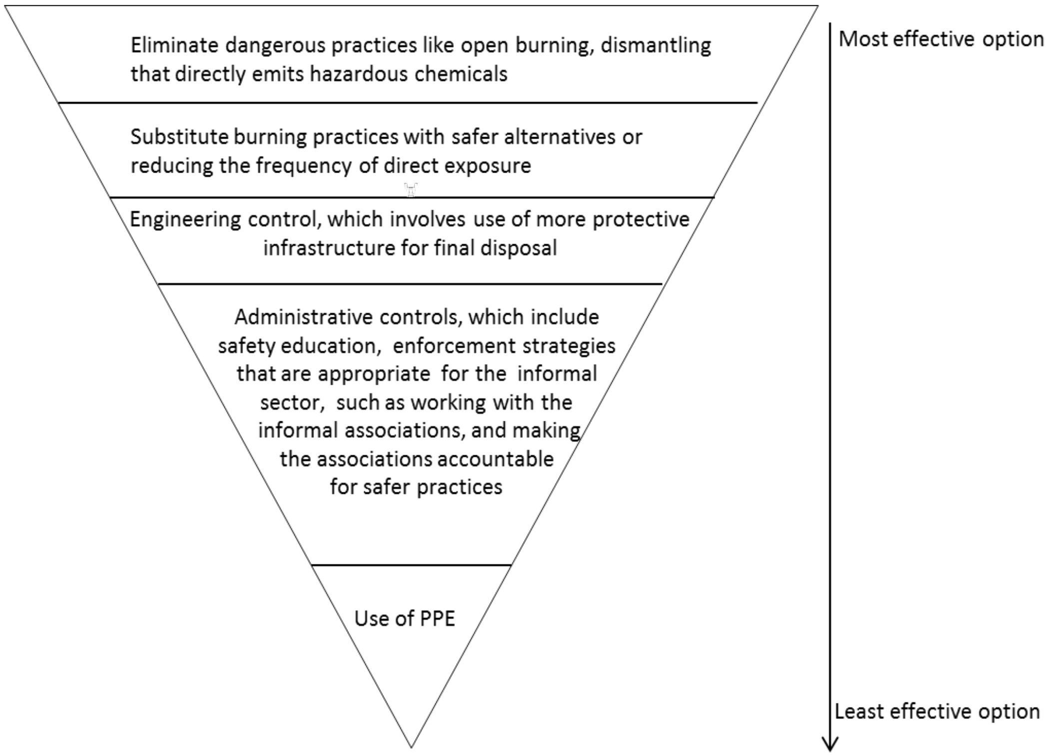


Figure 6.10. Hierachical Control at the Informal E-waste Recycling Sites (modified from OSHA 2016).

6.4.3 Conclusions

Our study is one of the few studies to estimate the total non-cancer effects and cancer risks of e-waste chemical (organic and inorganic) that e-waste workers and people around the e-waste recycling vicinity may be exposed to. The e-waste workers are prone to both adverse non-carcinogenic and carcinogenic health risks with dermal contact being the most important exposure route, followed by ingestion, while exposure via inhalation is the least important exposure route. This is even more worrisome as previous studies revealed that e-waste workers have poor work practices and low awareness of the health risks associated with informal e-waste recycling. These sobering findings call for the need for urgent action by both national and international govenments. There is a need for more appropriate e-waste management regulations that consider maximum participation of the informal e-waste workers to ensure a more sustainable improvement and development in this sector.

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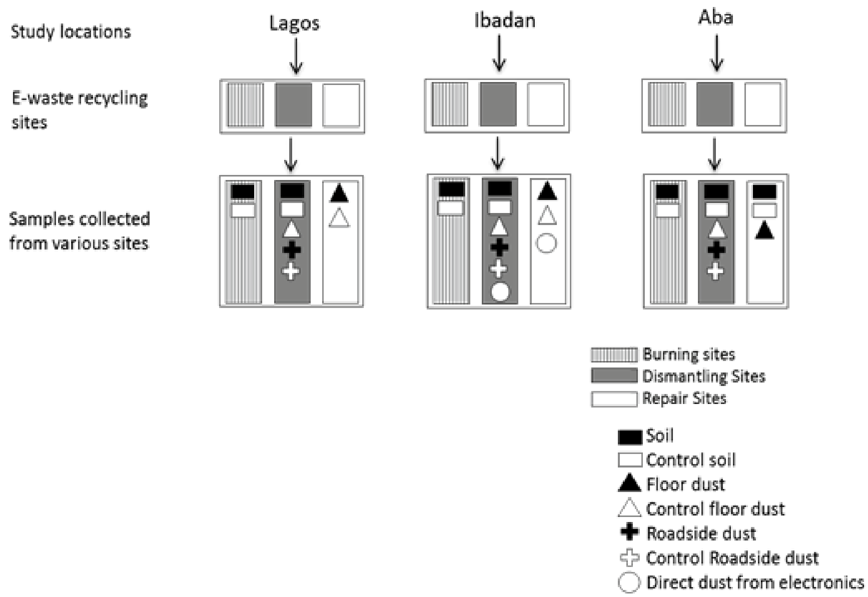
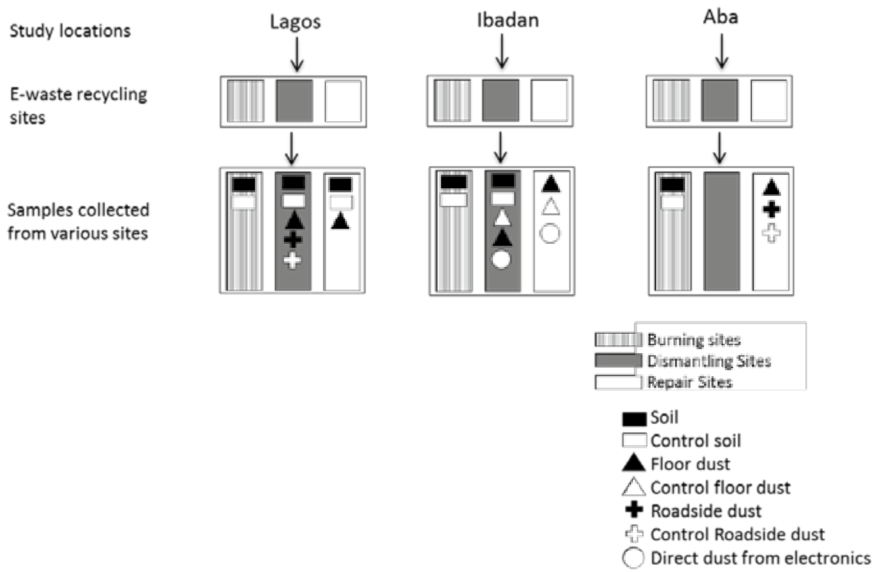


Supplementary Figure 6.1a. Flow Diagram of Sample Collection for Metal Analysis in the Study Locations



Supplementary Figure 6.1b. Flow Diagram of Sample Collection for PBDEs Analysis in the Study Locations

Supplementary Table 6.1: Median PBDE Concentrations (mg/kg) and Exeedance of Concentrations in Soil and Dusts across various E-waste Sites in Lagos

	Top Soil 0-10cm							Floor dust (control soil)				Roadside dust	
PBDE	Control	Burning sites		Dismantling sites		Repair sites		Dismantling sites		Repair sites		Dismantling sites	
	Median	Median	Exceed	Median	Exceed	Median	Ex	Median	Exceed	Median	Exceed	Median	Exceed
BDE-17	0	3.71		0.08		0.03		0.13		0.02		0.12	
BDE-28	0.005	40.54	8108	0.96	192	0.02	4	0.9	176	0.5	100	0.18	36.00
BDE-71	0.12	433..16	3610	9.4	78	0.13	1.08	23.3	194	1.6	13	8.1	67.50
BDE-47	0.04	17.05	426	3.67	92	0.1	2.50	6.3	158	0.54	14	8.02	200.50
BDE-66	0.02	8.42	421	1.49	75	0.04	2.00	1.4	70	0.14	7	0.61	30.50
BDE-100	0.06	86.02	1434	1.4	23	0.31	5.17	4.1	68	0.4	6.7	4.44	74.00
BDE-99	0.155	158.11	1020	10.83	70	0.53	3.42	15	97	1.8	12	19	122.58
BDE-85	0	22.22		0.04		0		0.21		0.01		0.47	
BDE-154	0.055	80.25	1460	2.68	49	0.21	3.82	5.4	98	0.41	7.45	2.5	45.45
BDE-153	0.085	64.19	755	9.93	117	0.24	2.82	8.9	105	1.9	22.35	8.2	96.47
BDE-138	0	3.24		0.14		0		0.82		0.12		0.29	
BDE-183	0.065	153.73	2365	11.41	176	0.2	3.08	17.6	270	5	77	10.76	165.54
BDE-190	0.06	164.12	2735	4.31	72	0.19	3.17	3.3	55	0.44	7.33	1.19	19.83
BDE-208	0.12	497.38	4145	8.66	72	0.1	0.83	6.33	53	3	25	3.28	27.33
BDE-207	0.25	952.29	3809	21.03	84	0.17	0.68	18.8	75	5.7	23	9.37	37.48
BDE-206	0.145	626.79	4323	8.72	60	0.07	0.48	15	104	2.8	19	9.49	65.45
BDE-209	3.42	17587	5143	1491	436	0.85	0.25	3009	880	432.74	127	961	280.99
$\sum_{16}$PBDE	1.2	3311	2759.35	88	73.33	2.34	1.95	125	104.17	25	20.83	99	82.50
$\sum_{17}$PBDE	4.67	20899	4475.07	1579	338.12	3.19	0.68	3134	671.092	452	96.79	1060	226.98
pH	8.04	7.7		7.89		7.87		8.4		8.31		8.29	
TOC	3.13	36.3		7.83		1.51		4.9		3.35		4.43	

Supplementary Table 6.2: Median Metals Concentrations (ng/kg) and Exeedances of the Concentraions in Soil and Dusts across various E-waste Sites in Lagos

	Top Soil 0-10cm							Floor dust (control soil)				Roadside dust	
Metals	Control	Burning sites		Dismantling sites		Repair sites		Dismantling sites		Repair sites		Dismantling sites	
	Median	Median	Exceed	Median	Exceed	Median	Exceed	Median	Exceed	Median	Exceed	Median	Exceed
V	43..8	24..2	0.6	50.85	1.16	10.2	0.23	38	0.87	26	0.59	35	0.8
Cr	70	68.7	1.0	103.2	1.47	49.3	0.70	78	1.11	57	0.81	62.5	0.9
Mn	116.5	160.1	1.4	694.9	5.96	81.4	0.70	680	5.84	301	2.58	426	3.7
Co	1.5	1.5	1.0	2.53	1.69	1.5	1.00	1.5	1.00	1.5	1.00	2.8	1.9
Ni	18	194.5	10.8	49.4	2.74	100	5.56	99.4	5.52	28	1.56	83	4.6
Cu	15	12590	839.3	759	50.60	27.6	1.84	766	51.07	82	5.47	236	15.7
Zn	44	3152	71.6	810.7	18.43	24.5	0.56	1342	30.50	312	7.09	924	21.0
Ga	9	1.45	0.2	15.4	1.71	4	0.44	7.8	0.87	4	0.44	5.8	0.6
Ge	0.25	0.25	1.0	0.43	1.72	0.8	3.20	0.6	2.40	0.25	1.00	2.1	8.4
As	0.8	83.2	104.0	4.93	6.16	3.6	4.50	5.7	7.13	0.25	0.31	13	16.3
Se	0.25	6	24.0	0.2	0.80	0.25	1.00	0.65	2.60	0.25	1.00	0.6	2.4
Mo	0.5	8.5	17.0	0.5	1.00	1.5	3.00	0.5	1.00	0.5	1.00	0.5	1.0
Ag	1	41.1	41.1	5.5	5.50	1	1.00	34.5	34.50	1.3	1.30	7.7	7.7
Cd	2.55	10.4	4.1	2.55	1.00	2.55	1.00	2.55	1.00	2.55	1.00	2.55	1.0
Sn	1.5	2722	1814.7	53.35	35.57	2.8	1.87	349	232.67	106	70.67	63	42.0
Sb	1.5	1544	1029.3	22.5	15.00	1.5	1.00	43	28.67	4	2.67	14	9.3
Te	0.5	1.5	3.0	1.5	3.00	1.5	3.00	1.5	3.00	1.5	3.00	1.5	3.0
Ba	78.4	1378	17.6	256.35	3.27	106.8	1.36	716	9.13	227	2.90	498	6.4
Hg	0.5	0.5	1.0	2.45	4.90	0.5	1.00	2.3	4.60	0.5	1.00	0.18	0.4
Tl	0.50	0.5	1.0	0.6	1.20	0.5	1.00	0.5	1.00	0.5	1.00	0.75	1.5
Pb	15.7	6358	405.0	199	12.68	12.2	0.78	277	17.64	57	3.63	374	23.8
Ta	17.8	0.5	0.0	19.9	1.12	18	1.01	6	0.34	16.4	0.92	21	1.2
Fe	11860	7373	0.6	31240	2.63	11000	0.93	32960	2.78	16610	1.40	24720	2.1
Ti	7696	4546	0.6	7804	1.01	5108	0.66		0.61	3059	0.40	4538	0.6

Supplementary Table 6.3: Median PBDE Concentrations (mg/kg) and Exeedances of the Concentrations in Soil and Dusts across various E-waste Sites in Ibadan

	Top Soil 0-10cm					Floor dust (control soil)		Direct dust			
PBDE	Control	Burning sites		Dismantling sites		Repair sites		Dismantling sites		Repair sites	
	Median	Median	Exceed	Median	Exceed	Median	Exceed	Median	Exceed	Median	Exceed
BDE-17	0	5.7		0		0.095		0.24		0.37	
BDE-28	0.03	18.5	616.7	0.04	1.33	1.03	34.33	1.24	41.33	3.8	127
BDE-71	0.05	40.14	802.8	0.4	8	8.78	176	18.21	364,2	23.2	464
BDE-47	0.12	83	692.5	0.2	1,7	4.12	34,33	64.6	538,33	14.62	121.83
BDE-66	0.04	25	625	0.04	1	1.1	27.5	5.4	135	2.53	63.25
BDE-100	0.1	20	200	0.17	1.7	1.51	15.1	24.2	242	4.8	48
BDE-99	0.27	107	396.3	0.42	1.6	10.64	39.41	151.2	560	26	95.2
BDE-85	0.005	8	1600	0	0	0.31	62	4.14	828	1.04	208
BDE-154	0.09	22.5	250	0.1	1.1	1.61	18	12.4	138	4.3	47.8
BDE-153	0.17	60	363.6	0.5	3.03	7.5	45.5	33.1	201	12.4	75.15
BDE-138	0	3.5		0		0,43		1.73		1.05	
BDE-183	0.07	38.7	553	1.2	17.14	14.5	206.57	16.7	238.6	15.5	221.42
BDE-190	0.03	32.4	1080	0.1	3.33	1.5	50	2.6	87	4.9	163.33
BDE-208	0.15	173.5	1157	1.2	8	25	164.7	14.2	94.5	25.3	168,33
BDE-207	0.27	367.3	1360	1.9	7.04	78.4	290.37	31.7	117.41	42	155.6
BDE-206	0.19	120	632	0.4	2.11	65	342.105	31.7	166.8	33.44	176
BDE-209	9	5850	650	13	1.44	8043	893.7	3181	353.4	1464	162.7
$\sum_{16}$PBDE	1,56	1124	720,51	5,1	3,269	237	151,92	413	264,74	221	142
$\sum_{17}$PBDE	10,54	6974	661,67	18,00	1,708	8280	785,58	3594	340,99	1685	160
pH	8.2	8.19		5		8.8		-		9	
TOC	3.6	16.78		5.8		5.29		-		18.56	

Supplementary Table 6.4: Median Metal Concentrations (mg/kg) and Exeedances of the Concentrations in Soil and Dusts across various E-waste Sites in Ibadan

	Top Soil 0-10cm					Floor dust (control soil)		Direct dust			
Metals	Control	Burning sites		Dismantling sites		Repair sites		Dismantling sites		Repair sites	
	Median	Median	Exceed	Median	Exceed	Median	Exceed	Median	Exceed	Median	Exceed
V	80	54	0.68	55.2	0.69	65	0.81	922	11.53	111	1.39
Cr	141	123	0.87	105	0.74	121	0.86	14.3	0.10	141	1.00
Mn	597	740	1.24	562	0.94	758	1.27	1607	2.69	797	1.34
Co	8.3	1.5	0.18	1.5	0.18	1.5	0.18	72.3	8.71	1.5	0.18
Ni	51.3	93	1.81	65	1.27	43	0.84	320	6.24	78	1.52
Cu	70	12749	182.13	1344	19.20	323	4.61	42	0.60	321	4.59
Zn	300	3327	11.09	1829	6.10	1152	3.84	122	0.41	2464	8.21
Ga	8.6	5.2	0.60	10	1.16	3	0.35	21	2.44	7.6	0.88
Ge	1.1	0.25	0.23	0.25	0.23	0.6	0.55	1	0.91	0.73	0.66
As	4	103	25.75	10.3	2.58	0.25	0.06	1.2	0.30	5	1.25
Se	0.5	26	52.00	4.4	8.80	1	2.00	0.25	0.50	0.9	1.80
Mo	4.2	8	1.90	7.2	1.71	0.6	0.14	1.3	0.31	2.7	0.64
Ag	14.2	16	1.13	8.5	0.60	5.5	0.39	1.35	0.10	15	1.06
Cd	2.55	7	2.75	2.55	1.00	2.55	1.00	2.55	1.00	2.7	1.06
Sn	44.4	1214	27.34	118	2.66	970	21.85	1.5	0.03	53	1.19
Sb	2	592	296.00	52	26.00	20	10.00	1.5	0.75	48	24.00
Te	1.5	1.5	1.00	1.5	1.00	1.5	1.00	1.5	1.00	1.5	1.00
Ba	638	930	1.46	589	0.92	469	0.74	90	0.14	1049	1.64
Hg	1.1	4.6	4.18	1.3	1.18	0.7	0.64	0.5	0.45	2.7	2.45
Tl	0.9	10	11.11	0.8	0.89	0.7	0.78	0.5	0.56	2.25	2.50
Pb	305	21423	70.24	2455	8.05	950	3.11	0.5	0.00	451	1.48
Ta	21	0.5	0.02	14	0.67	16	0.76	18	0.86	36	1.71
Fe	35835	31435	0.88	50110	1.40	42540	1.19	175000	4.88	57365	1.60
Ti	5265	6595	1.25	4691	0.89	3478	0.66	53190	10.10	4958	0.94

Supplementary Table 6.5: Median PBDE Concentrations (mg/kg) and Exceedances of the Concentrations in Soil and Dusts across various E-waste Sites in Aba

Top Soil 0-10cm (control Roadside dust)				Floor dust (control roadside dust)		Roadside dust (control roadside dust)		
PBDE	**Control**	**Burning sites**		**Repair sites**		**Repair sites**		**Control**
	Median	**Median**	**Exceed**	**Median**	**Exceed**	**Median**	**Exceed**	
BDE-17	0	0.65	0	0.03	0	0.31	0	0.000
BDE-28	0.02	2.3	115	0.16	8	1.44	72.00	0.02
BDE-71	0.06	5.6	93.33	0.73	12.17	3.35	55.83	0.06
BDE-47	0.47	5.6	11.91	1.42	3.02	3.9	8.30	0.47
BDE-66	0.4	2.3	5.75	0.2	0.50	1.6	4.00	0.04
BDE-100	0.18	1.64	9.11	0.38	2.11	0.6	3.33	0.18
BDE-99	1.08	11.7	10.83	2.55	2.36	5.84	5.41	1.08
BDE-85	0.04	4.85	121.25	0.13	3.25	0	0.00	0.04
BDE-154	0.13	7.74	59.54	0.43	3.31	2.46	18.92	0.13
BDE-153	0.23	20.7	90.00	1.6	6.96	7.9	34.35	0.32
BDE-138	0.02	1.6	80.00	0.1	5.00	0.54	27.00	0.02
BDE-183	0.33	13.4	40.61	8.72	26.42	4.56	13.82	0.33
BDE-190	0.07	7.5	107.14	0.37	5.29	2.82	40.29	0.07
BDE-208	0.57	4.4	7.72	3.4	5.96	2.57	4.51	0.57
BDE-207	1.13	8.74	7.73	10	8.85	3.46	3.06	1.13
BDE-206	1.2	3.63	3.03	6	5.00	2.15	1.79	1.1
BDE-209	71.5	103.3	1.44	534	7.47	69	0.97	71.5
$\sum_{16}$PBDE	5.68	102.25	18.00	41.56	7.32	42	7.39	5.7
$\sum_{17}$PBDE	77.7	205.55	2.65	553.15	7.12	111.4	1.43	77.7
pH		7.52		8.11		8.1		8.17
TOC		16.11		2.46		1.5		1.44

Supplementary Table 6.6: Median Metal Concentrations (ng/kg) and Exceedances of the Concentrations in Soil and Dusts across various E-waste Sites in Aba

	Top Soil 0-10cm (control soil)					Floor dust (control soil)				Roadside dust (Roadside dust soil)	
PBDE	**Control**	**Burning sites**		**Dismantling sites**		**Dismantling sites**		**Repair sites**		**Dismantling sites**	
	Median	**Median**	**Exceed**	**Median**	**Exceed**	**Median**	**Exceed**	**Median**	**Exceed**	**Median**	**Exceed**
V	39	28	0.72	46	1.18	26	0.67	17	0.44	42	1.08
Cr	63	102	1.62	197	3.13	188	2.98	42	0.67	30	0.48
Mn	257	419	1.63	540	2.10	654	2.54	307	1.19	274	1.07
Co	1.5	1.5	1.00	1.5	1.00	1.5	1.00	1.5	1.00	1.5	1.00
Ni	20	86	4.30	153	7.65	149	7.45	23	1.15	16	0.80
Cu	21	4435	211.19	7880	375.24	13580	646.67	191	9.10	23	1.10
Zn	85	3553	41.80	5650	66.47	5401	63.54	474	5.58	119	1.40
Ga	10	10	1.00	14.5	1.45	15	1.50	1.8	0.18	4.7	0.47
Ge	0.5	0.7	1.40	0.25	0.50	0.25	0.50	0.25	0.50	0.25	0.50
As	2	24	12.00	40	20.00	71	35.50	0.25	0.13	0.25	0.13
Se	0.25	2.5	10.00	11.5	46.00	4	16.00	0.25	1.00	0.25	1.00
Mo	0.5	14	28.00	17	34.00	17.5	35.00	0.5	1.00	0.5	1.00
Ag	1	8	8.00	14.5	14.50	40	40.00	1	1.00	1	1.00
Cd	2.55	0.5	0.20	24	9.41	30	11.76	2.55	1.00	2.55	1.00
Sn	1.5	81	54.00	238	158.67	740	493.33	338	225.33	5.5	3.67
Sb	1.4	49	35.00	203	145.00	382	272.86	10	7.14	1.1	0.79
Te	1.5	1.5	1.00	1.5	1.00	1.5	1.00	1.5	1.00	1.5	1.00
Ba	60	973	16.22	3906	65.10	992	16.53	215	3.58	170	2.83
Hg	18.5	0.5	0.03	0.5	0.03	0.5	0.03	0.5	0.03	1	0.05
Tl	**0.9**	0.5	0.56	0.5	0.56	0.5	0.56	0.5	0.56	0.5	0.56
Pb	**0.5**	1505	3010.00	2271	4542.00	3770	7540.00	150	300.00	34	68.00
Ta	29	0.5	0.02	1	0.03	1	0.03	17	0.59	26	0.90
Fe	21710	51330	2.36	70090	3.23	97260	4.48	18860	0.87	17780	0.82
Ti	8314	5748	0.69	2608	0.31	4969	0.60	3850	0.46	5488	0.66

Supplementary Table 6.7: PBDEs Estimation of Average Daily Dose (ADD) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Lagos

	Top Soil 0-10cm									Floor dust (control soil)						Roadside dust		
PBDE	Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites			Repair sites		
	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}
BDE-17	1.4E-06	6.3E-15	2.0E-03	3.1E-08	1.4E-16	4.3E-05	1.2E-08	5.1E-17	1.6E-05	5.0E-08	2.2E-16	6.9E-05	7.7E-09	3.4E-17	1.1E-05	4.6E-08	2.0E-16	6.4E-05
BDE-28	1.6E-05	6.9E-14	2.2E-02	3.7E-07	1.6E-15	5.1E-04	7.7E-09	3.4E-17	1.1E-05	3.4E-07	1.5E-15	4.7E-04	1.9E-07	8.5E-16	2.7E-04	6.9E-08	3.0E-16	9.6E-05
BDE-71	1.7E-04	7.3E-13	2.3E-01	3.6E-06	1.6E-14	5.0E-03	5.0E-08	2.2E-16	6.9E-05	8.9E-06	3.9E-14	1.2E-02	6.1E-07	2.7E-15	8.5E-04	3.1E-06	1.4E-14	4.3E-03
BDE-47	6.5E-06	2.9E-14	9.1E-03	1.4E-06	6.2E-15	2.0E-03	3.8E-08	1.7E-16	5.3E-05	2.4E-06	1.1E-14	3.4E-03	2.1E-07	9.1E-16	2.9E-04	3.1E-06	1.4E-14	4.3E-03
BDE-66	3.2E-06	1.4E-14	4.5E-03	5.7E-07	2.5E-15	7.9E-04	1.5E-08	6.8E-17	2.1E-05	5.4E-07	2.4E-15	7.5E-04	5.4E-08	2.4E-16	7.5E-05	2.3E-07	1.0E-15	3.2E-04
BDE-100	3.3E-05	1.5E-13	4.6E-02	5.4E-07	2.4E-15	7.5E-04	1.2E-07	5.3E-16	1.7E-04	1.6E-06	6.9E-15	2.2E-03	1.5E-07	6.8E-16	2.1E-04	1.7E-06	7.5E-15	2.4E-03
BDE-99	6.1E-05	2.7E-13	8.4E-02	4.2E-06	1.8E-14	5.8E-03	2.0E-07	9.0E-16	2.8E-04	5.8E-06	2.6E-14	8.0E-03	6.9E-07	3.0E-15	9.6E-04	7.3E-06	3.2E-14	1.0E-02
BDE-85	8.5E-06	3.8E-14	1.2E-02	1.5E-08	6.8E-17	2.1E-05	0.0E+00	0.0E+00	0.0E+00	8.1E-08	3.6E-16	1.1E-04	3.8E-09	1.7E-17	5.3E-06	1.8E-07	8.0E-16	2.5E-04
BDE-154	3.1E-05	1.4E-13	4.3E-02	1.0E-06	4.5E-15	1.4E-03	8.1E-08	3.6E-16	1.1E-04	2.1E-06	9.2E-15	2.9E-03	1.6E-07	6.9E-16	2.2E-04	9.6E-07	4.2E-15	1.3E-03
BDE-153	2.5E-05	1.1E-13	3.4E-02	3.8E-06	1.7E-14	5.3E-03	9.2E-08	4.1E-16	1.3E-04	3.4E-06	1.5E-14	4.7E-03	7.3E-07	3.2E-15	1.0E-03	3.1E-06	1.4E-14	4.4E-03
BDE-138	1.2E-06	5.5E-15	1.7E-03	5.4E-08	2.4E-16	7.5E-05	0.0E+00	0.0E+00	0.0E+00	3.1E-07	1.4E-15	4.4E-04	4.6E-08	2.0E-16	6.4E-05	1.1E-07	4.9E-16	1.5E-04
BDE-183	5.9E-05	2.6E-13	8.2E-02	4.4E-06	1.9E-14	6.1E-03	7.7E-08	3.4E-16	1.1E-04	6.7E-06	3.0E-14	9.4E-03	1.9E-06	8.5E-15	2.7E-03	4.1E-06	1.8E-14	5.7E-03
BDE-190	6.3E-05	2.8E-13	8.7E-02	1.7E-06	7.3E-15	2.3E-03	7.3E-08	3.2E-16	1.0E-04	1.3E-06	5.6E-15	1.8E-03	1.7E-07	7.5E-16	2.3E-04	4.6E-07	2.0E-15	6.3E-04
BDE-208	1.9E-04	8.4E-13	2.6E-01	3.3E-06	1.5E-14	4.6E-03	3.8E-08	1.7E-16	5.3E-05	2.4E-06	1.1E-14	3.4E-03	1.2E-06	5.1E-15	1.6E-03	1.3E-06	5.6E-15	1.7E-03
BDE-207	3.7E-04	1.6E-12	5.1E-01	8.1E-06	3.6E-14	1.1E-02	6.5E-08	2.9E-16	9.1E-05	7.2E-06	3.2E-14	1.0E-02	2.2E-06	9.7E-15	3.0E-03	3.6E-06	1.6E-14	5.0E-03
BDE-206	2.4E-04	1.1E-12	3.3E-01	3.3E-06	1.5E-14	4.6E-03	2.7E-08	1.2E-16	3.7E-05	5.8E-06	2.6E-14	8.0E-03	1.1E-06	4.7E-15	1.5E-03	3.6E-06	1.6E-14	5.1E-03
BDE-209	6.8E-03	3.0E-11	9.4E+00	5.7E-04	2.5E-12	7.9E-01	3.3E-07	1.4E-15	4.5E-04	1.2E-03	5.1E-12	1.6E+00	1.7E-04	7.3E-13	2.3E-01	3.7E-04	1.6E-12	5.1E-01
∑PBDE	**8.0E-03**	**3.5E-11**	**1.1E+01**	**6.1E-04**	**2.7E-12**	**8.4E-01**	**1.2E-06**	**5.4E-15**	**1.7E-03**	**1.2E-03**	**5.3E-12**	**1.7E+00**	**1.8E-04**	**7.7E-13**	**2.4E-01**	**4.0E-04**	**1.8E-12**	**5.6E-01**

Supplementary Table 6.8:PBDEs Estimation of Average Daily Dose (ADD) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Ibadan

	Top Soil 0-10cm						Floor dust (control soil)			Direct dust					
PBDE	Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites		
	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}
BDE-17	2.2E-06	9.7E-15	3.0E-03	0.0E+00	0.0E+00	0.0E+00	3.6E-08	1.6E-16	5.1E-05	9.2E-08	4.1E-16	1.3E-04	1.4E-07	6.3E-16	2.0E-04
BDE-28	7.1E-06	3.1E-14	9.9E-03	1.5E-08	6.8E-17	2.1E-05	4.0E-07	1.7E-15	5.5E-04	4.8E-07	2.1E-15	6.6E-04	1.5E-06	6.4E-15	2.0E-03
BDE-71	1.5E-05	6.8E-14	2.1E-02	1.5E-07	6.8E-16	2.1E-04	3.4E-06	1.5E-14	4.7E-03	7.0E-06	3.1E-14	9.7E-03	8.9E-06	3.9E-14	1.2E-02
BDE-47	3.2E-05	1.4E-13	4.4E-02	7.7E-08	3.4E-16	1.1E-04	1.6E-06	7.0E-15	2.2E-03	2.5E-05	1.1E-13	3.4E-02	5.6E-06	2.5E-14	7.8E-03
BDE-66	9.6E-06	4.2E-14	1.3E-02	1.5E-08	6.8E-17	2.1E-05	4.2E-07	1.9E-15	5.9E-04	2.1E-06	9.1E-15	2.9E-03	9.7E-07	4.3E-15	1.3E-03
BDE-100	7.7E-06	3.4E-14	1.1E-02	6.5E-08	2.9E-16	9.1E-05	5.8E-07	2.6E-15	8.0E-04	9.3E-06	4.1E-14	1.3E-02	1.8E-06	8.1E-15	2.6E-03
BDE-99	4.1E-05	1.8E-13	5.7E-02	1.6E-07	7.1E-16	2.2E-04	4.1E-06	1.8E-14	5.7E-03	5.8E-05	2.6E-13	8.1E-02	9.9E-06	4.4E-14	1.4E-02
BDE-85	3.1E-06	1.4E-14	4.3E-03	0.0E+00	0.0E+00	0.0E+00	1.2E-07	5.3E-16	1.7E-04	1.6E-06	7.0E-15	2.2E-03	4.0E-07	1.8E-15	5.5E-04
BDE-154	8.6E-06	3.8E-14	1.2E-02	3.8E-08	1.7E-16	5.3E-05	6.2E-07	2.7E-15	8.6E-04	4.8E-06	2.1E-14	6.6E-03	1.7E-06	7.3E-15	2.3E-03
BDE-153	2.3E-05	1.0E-13	3.2E-02	1.9E-07	8.5E-16	2.7E-04	2.9E-06	1.3E-14	4.0E-03	1.3E-05	5.6E-14	1.8E-02	4.8E-06	2.1E-14	6.6E-03
BDE-138	1.3E-06	5.9E-15	1.9E-03	0.0E+00	0.0E+00	0.0E+00	1.7E-07	7.3E-16	2.3E-04	6.6E-07	2.9E-15	9.2E-04	4.0E-07	1.8E-15	5.6E-04
BDE-183	1.5E-05	6.6E-14	2.1E-02	4.6E-07	2.0E-15	6.4E-04	5.6E-06	2.4E-14	7.7E-03	6.4E-06	2.8E-14	8.9E-03	6.0E-06	2.6E-14	8.3E-03
BDE-190	1.2E-05	5.5E-14	1.7E-02	3.8E-08	1.7E-16	5.3E-05	5.8E-07	2.5E-15	8.0E-04	1.0E-06	4.4E-15	1.4E-03	1.9E-06	8.3E-15	2.6E-03
BDE-208	6.7E-05	2.9E-13	9.2E-02	4.6E-07	2.0E-15	6.4E-04	9.5E-06	4.2E-14	1.3E-02	5.4E-06	2.4E-14	7.5E-03	9.7E-06	4.3E-14	1.3E-02
BDE-207	1.4E-04	6.2E-13	2.0E-01	7.3E-07	3.2E-15	1.0E-03	3.0E-05	1.3E-13	4.2E-02	1.2E-05	5.4E-14	1.7E-02	1.6E-05	7.1E-14	2.2E-02
BDE-206	4.6E-05	2.0E-13	6.4E-02	1.5E-07	6.8E-16	2.1E-04	2.5E-05	1.1E-13	3.5E-02	1.2E-05	5.4E-14	1.7E-02	1.3E-05	5.7E-14	1.8E-02
BDE-209	2.2E-03	9.9E-12	3.1E+00	5.0E-06	2.2E-14	6.9E-03	3.1E-03	1.4E-11	4.3E+00	1.2E-02	5.4E-11	1.7E+01	5.6E-04	2.5E-12	7.8E-01
∑PBDE	**2.7E-03**	**1.2E-11**	**3.7E+00**	**7.6E-06**	**3.3E-14**	**1.0E-02**	**3.2E-03**	**1.4E-11**	**4.4E+00**	**1.2E-02**	**5.5E-11**	**1.7E+01**	**6.4E-04**	**2.8E-12**	**8.9E-01**

Supplementary Table 6.9: PBDEs Estimation of Average Daily Dose (ADD) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Aba

	Top Soil 0-10cm			Floor dust (control soil)			Roadside dust		
PBDE	**Burning sites**			**Repair sites**			**Repair sites**		
	ADD_{ing}	**ADD_{inh}**	**ADD_{der}**	**ADD_{ing}**	**ADD_{inh}**	**ADD_{der}**	**ADD_{ing}**	**ADD_{inh}**	**ADD_{der}**
BDE-17	2.5E-07	1.1E-15	3.5E-04	1.2E-08	5.1E-17	1.6E-05	1.2E-07	5.3E-16	1.7E-04
BDE-28	8.8E-07	3.9E-15	1.2E-03	6.1E-08	2.7E-16	8.5E-05	5.5E-07	2.4E-15	7.7E-04
BDE-71	2.2E-06	9.5E-15	3.0E-03	2.8E-07	1.2E-15	3.9E-04	1.3E-06	5.7E-15	1.8E-03
BDE-47	2.2E-06	9.5E-15	3.0E-03	5.5E-07	2.4E-15	7.6E-04	1.5E-06	6.6E-15	2.1E-03
BDE-66	8.8E-07	3.9E-15	1.2E-03	7.7E-08	3.4E-16	1.1E-04	6.1E-07	2.7E-15	8.5E-04
BDE-100	6.3E-07	2.8E-15	8.7E-04	1.5E-07	6.4E-16	2.0E-04	2.3E-07	1.0E-15	3.2E-04
BDE-99	4.5E-06	2.0E-14	6.2E-03	9.8E-07	4.3E-15	1.4E-03	2.2E-06	9.9E-15	3.1E-03
BDE-85	1.9E-06	8.2E-15	2.6E-03	5.0E-08	2.2E-16	6.9E-05	0.0E+00	0.0E+00	0.0E+00
BDE-154	3.0E-06	1.3E-14	4.1E-03	1.7E-07	7.3E-16	2.3E-04	9.4E-07	4.2E-15	1.3E-03
BDE-153	7.9E-06	3.5E-14	1.1E-02	6.1E-07	2.7E-15	8.5E-04	3.0E-06	1.3E-14	4.2E-03
BDE-138	6.1E-07	2.7E-15	8.5E-04	3.8E-08	1.7E-16	5.3E-05	2.1E-07	9.1E-16	2.9E-04
BDE-183	5.1E-06	2.3E-14	7.1E-03	3.3E-06	1.5E-14	4.6E-03	1.8E-06	7.7E-15	2.4E-03
BDE-190	2.9E-06	1.3E-14	4.0E-03	1.4E-07	6.3E-16	2.0E-04	1.1E-06	4.8E-15	1.5E-03
BDE-208	1.7E-06	7.5E-15	2.3E-03	1.3E-06	5.8E-15	1.8E-03	9.9E-07	4.4E-15	1.4E-03
BDE-207	3.4E-06	1.5E-14	4.7E-03	3.8E-06	1.7E-14	5.3E-03	1.3E-06	5.9E-15	1.8E-03
BDE-206	1.4E-06	6.1E-15	1.9E-03	2.3E-06	1.0E-14	3.2E-03	8.3E-07	3.6E-15	1.1E-03
BDE-209	4.0E-05	1.7E-13	5.5E-02	2.1E-04	9.0E-13	2.8E-01	2.6E-05	1.2E-13	3.7E-02
∑PBDE	**7.9E-05**	**3.5E-13**	**1.1E-01**	**2.2E-04**	**9.7E-13**	**3.0E-01**	**4.3E-05**	**1.9E-13**	**6.0E-02**

Supplementary Table 6.10: Metal Estimation of Average Daily Dose (ADD) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Lagos

	Top Soil 0-10cm									Floor dust (control soil)						Roadside dust		
Metals	Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites			Dismantling sites		
	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}
V	9.3E-06	4.1E-14	1.3E-02	2.0E-05	8.6E-14	2.7E-02	3.9E-06	1.7E-14	5.4E-03	1.5E-05	6.4E-14	2.0E-02	1.0E-05	4.4E-14	1.4E-02	1.3E-05	5.9E-14	1.9E-02
Cr	2.6E-05	1.2E-13	3.7E-02	4.0E-05	1.7E-13	5.5E-02	1.9E-05	8.4E-14	2.6E-02	3.0E-05	1.3E-13	4.2E-02	2.2E-05	9.7E-14	3.0E-02	2.4E-05	1.1E-13	3.3E-02
Mn	6.1E-05	2.7E-13	8.5E-02	2.7E-04	1.2E-12	3.7E-01	3.1E-05	1.4E-13	4.3E-02	2.6E-04	1.2E-12	3.6E-01	1.2E-04	5.1E-13	1.6E-01	1.6E-04	7.2E-13	2.3E-01
Co	5.8E-07	2.5E-15	8.0E-04	9.7E-07	4.3E-15	1.3E-03	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	1.1E-06	4.7E-15	1.5E-03
Ni	7.5E-05	3.3E-13	1.0E-01	1.9E-05	8.4E-14	2.6E-02	3.8E-05	1.7E-13	5.3E-02	3.8E-05	1.7E-13	5.3E-02	1.1E-05	4.7E-14	1.5E-02	3.2E-05	1.4E-13	4.4E-02
Cu	4.8E-03	2.1E-11	6.7E+00	2.9E-04	1.3E-12	4.0E-01	1.1E-05	4.7E-14	1.5E-02	2.9E-04	1.3E-12	4.1E-01	3.1E-05	1.4E-13	4.4E-02	9.1E-05	4.0E-13	1.3E-01
Zn	1.2E-03	5.3E-12	1.7E+00	3.1E-04	1.4E-12	4.3E-01	9.4E-06	4.2E-14	1.3E-02	5.2E-04	2.3E-12	7.1E-01	1.2E-04	5.3E-13	1.7E-01	3.5E-04	1.6E-12	4.9E-01
Ga	5.6E-07	2.5E-15	7.7E-04	5.9E-06	2.6E-14	8.2E-03	1.5E-06	6.8E-15	2.1E-03	3.0E-06	1.3E-14	4.2E-03	1.5E-06	6.8E-15	2.1E-03	2.2E-06	9.8E-15	3.1E-03
Ge	9.6E-08	4.2E-16	1.3E-04	1.7E-07	7.3E-16	2.3E-04	3.1E-07	1.4E-15	4.3E-04	2.3E-07	1.0E-15	3.2E-04	9.6E-08	4.2E-16	1.3E-04	8.1E-07	3.6E-15	1.1E-03
As	3.2E-05	1.4E-13	1.3E-02	1.9E-06	8.4E-15	7.9-04	1.4E-06	6.1E-15	5.8E-04	2.2E-06	9.7E-15	9.1E-04	9.6E-08	4.2E-16	4.0E-05	5.0E-06	2.2E-14	2.1E-03
Se	2.3E-06	1.0E-14	3.2E-03	7.7E-08	3.4E-16	1.1E-04	9.6E-08	4.2E-16	1.3E-04	2.5E-07	1.1E-15	3.5E-04	9.6E-08	4.2E-16	1.3E-04	2.3E-07	1.0E-15	3.2E-04
Mo	3.3E-06	1.4E-14	4.5E-03	1.9E-07	8.5E-16	2.7E-04	5.8E-07	2.5E-15	8.0E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04
Ag	1.6E-05	7.0E-14	2.2E-02	2.1E-06	9.3E-15	2.9E-03	3.8E-07	1.7E-15	5.3E-04	1.3E-05	5.8E-14	1.8E-02	5.0E-07	2.2E-15	6.9E-04	3.0E-06	1.3E-14	4.1E-03
Cd	4.0E-06	1.8E-14	5.5E-05	9.8E-07	4.3E-15	1.4E-05	9.8E-07	4.3E-15	1.4E-05	9.8E-07	4.3E-15	1.4E-05	9.8E-07	4.3E-15	1.4E-05	9.8E-07	4.3E-15	1.4E-05
Sn	1.0E-03	4.6E-12	1.4E+00	2.0E-05	9.0E-14	2.8E-02	1.1E-06	4.7E-15	1.5E-03	1.3E-04	5.9E-13	1.9E-01	4.1E-05	1.8E-13	5.6E-02	2.4E-05	1.1E-13	3.4E-02
Sb	5.9E-04	2.6E-12	8.2E-01	8.6E-06	3.8E-14	1.2E-02	5.8E-07	2.5E-15	8.0E-04	1.7E-05	7.3E-14	2.3E-02	1.5E-06	6.8E-15	2.1E-03	5.4E-06	2.4E-14	7.5E-03
Te	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04
Ba	5.3E-04	2.3E-12	7.3E-01	9.8E-05	4.3E-13	1.4E-01	4.1E-05	1.8E-13	5.7E-02	2.7E-04	1.2E-12	3.8E-01	8.7E-05	3.8E-13	1.2E-01	1.9E-04	8.4E-13	2.7E-01
Hg	1.9E-07	8.5E-16	2.7E-04	9.4E-07	4.2E-15	1.3E-03	1.9E-07	8.5E-16	2.7E-04	8.8E-07	3.9E-15	1.2E-03	1.9E-07	8.5E-16	2.7E-04	6.9E-08	3.0E-16	9.6E-05
Tl	1.9E-07	8.5E-16	2.7E-04	2.3E-07	1.0E-15	3.2E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	2.9E-07	1.3E-15	4.0E-04
Pb	2.4E-03	1.1E-11	3.4E+00	7.6E-05	3.4E-13	1.1E-01	4.7E-06	2.1E-14	6.5E-03	1.1E-04	4.7E-13	1.5E-01	2.2E-05	9.7E-14	3.0E-02	1.4E-04	6.3E-13	2.0E-01
Ta	1.9E-07	8.5E-16	2.7E-04	7.6E-06	3.4E-14	1.1E-02	6.9E-06	3.0E-14	9.6E-03	2.3E-06	1.0E-14	3.2E-03	6.3E-06	2.8E-14	8.7E-03	8.1E-06	3.6E-14	1.1E-02
Fe	2.8E-03	1.2E-11	3.9E+00	1.2E-02	5.3E-11	1.7E+01	4.2E-03	1.9E-11	5.9E+00	1.3E-02	5.6E-11	1.8E+01	6.4E-03	2.8E-11	8.8E+00	9.5E-03	4.2E-11	1.3E+01
Ti	1.7E-03	7.7E-12	2.4E+00	3.0E-03	1.3E-11	4.2E+00	2.0E-03	8.7E-12	2.7E+00	1.8E-03	8.0E-12	2.5E+00	1.2E-03	5.2E-12	1.6E+00	1.7E-03	7.7E-12	2.4E+00

Supplementary Table 6.11: Metal Average Daily Dose (ADD) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Ibadan

	Top Soil 0-10cm						Floor dust (control soil)			Direct dust					
Metals	**Burning sites**			**Dismantling sites**			**Repair sites**			**Dismantling sites**			**Repair sites**		
	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}
V	2.1E-05	9.1E-14	2.9E-02	2.1E-05	9.4E-14	2.9E-02	2.5E-05	1.1E-13	3.5E-02	3.5E-04	1.6E-12	4.9E-01	4.3E-05	1.9E-13	5.9E-02
Cr	4.7E-05	2.1E-13	6.6E-02	4.0E-05	1.8E-13	5.6E-02	4.6E-05	2.0E-13	6.4E-02	5.5E-06	2.4E-14	7.6E-03	5.4E-05	2.4E-13	7.5E-02
Mn	2.8E-04	1.3E-12	3.9E-01	2.2E-04	9.5E-13	3.0E-01	2.9E-04	1.3E-12	4.0E-01	6.2E-04	2.7E-12	8.6E-01	3.1E-04	1.4E-12	4.2E-01
Co	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	2.8E-05	1.2E-13	3.9E-02	5.8E-07	2.5E-15	8.0E-04
Ni	3.6E-05	1.6E-13	5.0E-02	2.5E-05	1.1E-13	3.5E-02	1.7E-05	7.3E-14	2.3E-02	1.2E-04	5.4E-13	1.7E-01	3.0E-05	1.3E-13	4.2E-02
Cu	4.9E-03	2.2E-11	6.8E+00	5.2E-04	2.3E-12	7.2E-01	1.2E-04	5.5E-13	1.7E-01	1.6E-05	7.1E-14	2.2E-02	1.2E-04	5.4E-13	1.7E-01
Zn	1.3E-03	5.6E-12	1.8E+00	7.0E-04	3.1E-12	9.7E-01	4.4E-04	2.0E-12	6.1E-01	4.7E-05	2.1E-13	6.5E-02	9.5E-04	4.2E-12	1.3E+00
Ga	2.0E-06	8.8E-15	2.8E-03	3.8E-06	1.7E-14	5.3E-03	1.2E-06	5.1E-15	1.6E-03	8.1E-06	3.6E-14	1.1E-02	2.9E-06	1.3E-14	4.0E-03
Ge	9.6E-08	4.2E-16	1.3E-04	9.6E-08	4.2E-16	1.3E-04	2.3E-07	1.0E-15	3.2E-04	3.8E-07	1.7E-15	5.3E-04	2.8E-07	1.2E-15	3.9E-04
As	4.0E-05	1.7E-13	1.6E-02	4.0E-06	1.7E-14	1.6E-03	9.6E-08	4.2E-16	4.0E-05	4.6E-07	2.0E-15	1.9E-04	1.9E-06	8.5E-15	8.0E-04
Se	1.0E-05	4.4E-14	1.4E-02	1.7E-06	7.5E-15	2.3E-03	3.8E-07	1.7E-15	5.3E-04	9.6E-08	4.2E-16	1.3E-04	3.5E-07	1.5E-15	4.8E-04
Mo	3.1E-06	1.4E-14	4.3E-03	2.8E-06	1.2E-14	3.8E-03	2.3E-07	1.0E-15	3.2E-04	5.0E-07	2.2E-15	6.9E-04	1.0E-06	4.6E-15	1.4E-03
Ag	6.1E-06	2.7E-14	8.5E-03	3.3E-06	1.4E-14	4.5E-03	2.1E-06	9.3E-15	2.9E-03	5.2E-07	2.3E-15	7.2E-04	5.8E-06	2.5E-14	8.0E-03
Cd	2.7E-06	1.2E-14	3.7E-05	9.8E-07	4.3E-15	1.4E-05	9.8E-07	4.3E-15	1.4E-05	9.8E-07	4.3E-15	1.4E-05	1.0E-06	4.6E-15	1.4E-05
Sn	4.7E-04	2.1E-12	6.5E-01	4.5E-05	2.0E-13	6.3E-02	3.7E-04	1.6E-12	5.2E-01	5.8E-07	2.5E-15	8.0E-04	2.0E-05	9.0E-14	2.8E-02
Sb	2.3E-04	1.0E-12	3.2E-01	2.0E-05	8.8E-14	2.8E-02	7.7E-06	3.4E-14	1.1E-02	5.8E-07	2.5E-15	8.0E-04	1.8E-05	8.1E-14	2.6E-02
Te	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04
Ba	3.6E-04	1.6E-12	5.0E-01	2.3E-04	1.0E-12	3.1E-01	1.8E-04	7.9E-13	2.5E-01	3.5E-05	1.5E-13	4.8E-02	4.0E-04	1.8E-12	5.6E-01
Hg	1.8E-06	7.8E-15	2.4E-03	5.0E-07	2.2E-15	6.9E-04	2.7E-07	1.2E-15	3.7E-04	1.9E-07	8.5E-16	2.7E-04	1.0E-06	4.6E-15	1.4E-03
Tl	3.8E-06	1.7E-14	5.3E-03	3.1E-07	1.4E-15	4.3E-04	2.7E-07	1.2E-15	3.7E-04	1.9E-07	8.5E-16	2.7E-04	8.6E-07	3.8E-15	1.2E-03
Pb	8.2E-03	3.6E-11	1.1E+01	9.4E-04	4.2E-12	1.3E+00	3.6E-04	1.6E-12	5.1E-01	1.9E-07	8.5E-16	2.7E-04	1.7E-04	7.6E-13	2.4E-01
Ta	1.9E-07	8.5E-16	2.7E-04	5.4E-06	2.4E-14	7.5E-03	6.1E-06	2.7E-14	8.5E-03	6.9E-06	3.0E-14	9.6E-03	1.4E-05	6.1E-14	1.9E-02
Fe	1.2E-02	5.3E-11	1.7E+01	1.9E-02	8.5E-11	2.7E+01	1.6E-02	7.2E-11	2.3E+01	6.7E-02	3.0E-10	9.3E+01	2.2E-02	9.7E-11	3.1E+01
Ti	2.5E-03	1.1E-11	3.5E+00	1.8E-03	7.9E-12	2.5E+00	1.3E-03	5.9E-12	1.9E+00	2.0E-02	9.0E-11	2.8E+01	1.9E-03	8.4E-12	2.6E+00

Supplementary Table 6.12: Metal Average Daily Dose (ADD) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Aba

	Top Soil 0-10cm						Floor dust						Roadside dust		
Metals	Burning sites			Dismantling sites			Dismantling sites			Repair sites					
	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}	ADD_{ing}	ADD_{inh}	ADD_{der}
V	1.1E-05	4.7E-14	1.5E-02	1.8E-05	7.8E-14	2.4E-02	1.0E-05	4.4E-14	1.4E-02	6.5E-06	2.9E-14	9.1E-03	1.6E-05	7.1E-14	2.2E-02
Cr	3.9E-05	1.7E-13	5.4E-02	7.6E-05	3.3E-13	1.0E-01	7.2E-05	3.2E-13	1.0E-01	1.6E-05	7.1E-14	2.2E-02	1.2E-05	5.1E-14	1.6E-02
Mn	1.6E-04	7.1E-13	2.2E-01	2.1E-04	9.1E-13	2.9E-01	2.5E-04	1.1E-12	3.5E-01	1.2E-04	5.2E-13	1.6E-01	1.1E-04	4.6E-13	1.5E-01
Co	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04
Ni	3.3E-05	1.5E-13	4.6E-02	5.9E-05	2.6E-13	8.1E-02	5.7E-05	2.5E-13	7.9E-02	8.8E-06	3.9E-14	1.2E-02	6.1E-06	2.7E-14	8.5E-03
Cu	1.7E-03	7.5E-12	2.4E+00	3.0E-03	1.3E-11	4.2E+00	5.2E-03	2.3E-11	7.2E+00	7.3E-05	3.2E-13	1.0E-01	8.8E-06	3.9E-14	1.2E-02
Zn	1.4E-03	6.0E-12	1.9E+00	2.2E-03	9.6E-12	3.0E+00	2.1E-03	9.1E-12	2.9E+00	1.8E-04	8.0E-13	2.5E-01	4.6E-05	2.0E-13	6.3E-02
Ga	3.8E-06	1.7E-14	5.3E-03	5.6E-06	2.5E-14	7.7E-03	5.8E-06	2.5E-14	8.0E-03	6.9E-07	3.0E-15	9.6E-04	1.8E-06	8.0E-15	2.5E-03
Ge	2.7E-07	1.2E-15	3.7E-04	9.6E-08	4.2E-16	1.3E-04	9.6E-08	4.2E-16	1.3E-04	9.6E-08	4.2E-16	1.3E-04	9.6E-08	4.2E-16	1.3E-04
As	9.2E-06	4.1E-14	3.8E-03	1.5E-05	6.8E-14	6.4E-03	2.7E-05	1.2E-13	1.1E-02	9.6E-08	4.2E-16	4.0E-05	9.6E-08	4.2E-16	4.0E-05
Se	9.6E-07	4.2E-15	1.3E-03	4.4E-06	1.9E-14	6.1E-03	1.5E-06	6.8E-15	2.1E-03	9.6E-08	4.2E-16	1.3E-04	9.6E-08	4.2E-16	1.3E-04
Mo	5.4E-06	2.4E-14	7.5E-03	6.5E-06	2.9E-14	9.1E-03	6.7E-06	3.0E-14	9.3E-03	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04
Ag	3.1E-06	1.4E-14	4.3E-03	5.6E-06	2.5E-14	7.7E-03	1.5E-05	6.8E-14	2.1E-02	3.8E-07	1.7E-15	5.3E-04	3.8E-07	1.7E-15	5.3E-04
Cd	1.9E-07	8.5E-16	2.7E-04	9.2E-06	4.1E-14	1.3E-02	1.2E-05	5.1E-14	1.6E-02	9.8E-07	4.3E-15	1.4E-03	9.8E-07	4.3E-15	1.4E-03
Sn	3.1E-05	1.4E-13	4.3E-02	9.1E-05	4.0E-13	1.3E-01	2.8E-04	1.3E-12	3.9E-01	1.3E-04	5.7E-13	1.8E-01	2.1E-06	9.3E-15	2.9E-03
Sb	1.9E-05	8.3E-14	2.6E-02	7.8E-05	3.4E-13	1.1E-01	1.5E-04	6.5E-13	2.0E-01	3.8E-06	1.7E-14	5.3E-03	4.2E-07	1.9E-15	5.9E-04
Te	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04	5.8E-07	2.5E-15	8.0E-04
Ba	3.7E-04	1.6E-12	5.2E-01	1.5E-03	6.6E-12	2.1E+00	3.8E-04	1.7E-12	5.3E-01	8.3E-05	3.6E-13	1.1E-01	6.5E-05	2.9E-13	9.1E-02
Hg	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	3.8E-07	1.7E-15	5.3E-04
Tl	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04	1.9E-07	8.5E-16	2.7E-04
Pb	5.8E-04	2.5E-12	8.0E-01	8.7E-04	3.8E-12	1.2E+00	1.4E-03	6.4E-12	2.0E+00	5.8E-05	2.5E-13	8.0E-02	1.3E-05	5.8E-14	1.8E-02
Ta	1.9E-07	8.5E-16	2.7E-04	3.8E-07	1.7E-15	5.3E-04	3.8E-07	1.7E-15	5.3E-04	6.5E-06	2.9E-14	9.1E-03	1.0E-05	4.4E-14	1.4E-02
Fe	2.0E-02	8.7E-11	2.7E+01	2.7E-02	1.2E-10	3.7E+01	3.7E-02	1.6E-10	5.2E+01	7.2E-03	3.2E-11	1.0E+01	6.8E-03	3.0E-11	9.5E+00
Ti	2.2E-03	9.7E-12	3.1E+00	1.0E-03	4.4E-12	1.4E+00	1.9E-03	8.4E-12	2.6E+00	1.5E-03	6.5E-12	2.1E+00	2.1E-03	9.3E-12	2.9E+00

Supplementary Table 6.13: Hazard Quotient (HQ) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Lagos

PBDE	RfD	Top Soil 0-10cm									Floor dust (control soil)						Roadside dust		
		Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites			Dismantling sites		
		HQing	HQinh	HQder	HQing	HQinh	HQder	HQing	HQinh	HQder	HQing	HQinh	HQder	HQing	HQinh	HQder	HQing	HQinh	HQder
BDE-47	1.00E-04	6.5E-05		9.1E-02	1.41E-05		2.0E-02	3.8E-07		5.3E-04	2.42E-05		3.36E-02	2.07E-06		2.88^{E}-03	3.08^{E}-05		4.27^{E}-02
BDE-99	1.00E-04	6.1E-04		8.4E-01	4.16E-05		5.8E-02	2.0E-06		2.8E-03	5.80E-05		8.04E-02	6.91E-06		9.59^{E}-03	7.30^{E}-05		1.01E-01
BDE-153	2.00E-04	1.2E-04		1.7E-01	1.91E-05		2.6E-02	4.6E-01		6.4E-04	1.71E-05		2.37E-02	3.65E-06		5.06^{E}-03	1.57^{E}-05		2.18E-02
BDE-209	7.00E-03	9.6E-04		1.3E+00	8.18E-05		1.1E-01	4.7E-07		6.5E-05	1.65E-04		2.29E-01	2.37E-05		3.29^{E}-02	5.27^{E}-05		7.31E-02
∑HQ=HI		**1.76E**-03		**2.4E+00**	**1.57E**-04		**2.2E**-01	**2.93E**-06		**4.06E**-03	**2.64E**-04		**3.67E**-01	**3.64E**-05		**5.04^{E}-02**	**1.72^{E}-04**		**2.39E**-01

Supplementary Table 6.14: Hazard Quotient (HQ) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Ibadan

PBDE	RfD	Top Soil 0-10cm						Floor dust (control soil)			Direct dust					
		Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites		
		HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}
BDE-47	1.00E-04	3.2E-01		4.4+02	7.7E-04		1.1E+00	1.6E-02		2.2E+01	2.48E-01		3.4E+02	5.61E-02		7.8E+01
BDE-99	1.00E-04	4.1E-01		5.7E+02	1.6E-03		2.2E+00	4.1E-02		5.7E+01	5.81E-01		8.1E+02	9.87E-02		1.4E+02
BDE-153	2.00E-04	1.2E-01		1.6E+02	9.6E-04		1.3E+00	1.4E-02		2.0E+01	6.35E-02		8.8E+01	2.38E-02		3.3E+01
BDE-209	7.00E-03	3.2E-01		4.5E-02	7.1E-04		9.9E-01	4.4E-01		6.1E+02	1.74E+00		2.4E+03	8.03E-02		1.1E+02
∑HQ=HI		**1.2E+00**		**1.6E+03**	**4.1E-03**		**5.6E+00**	**5.1E-01**		**7.1E+02**	**2.64E+00**		**3.7E+03**	**2.59E-01**		**3.6E+02**

Supplementary Table 6.15: Hazard Quotient (HQ) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Aba

		Top Soil 0-10cm			Floor dust (control soil)			Roadside dust		
PBDE	**RfD**	**Burning sites**			**Repair sites**			**Repair sites**		
		HQ_{ing}	**R_{ing}**	**R_{der}**	**HQ_{ing}**	**R_{ing}**	**R_{der}**	**HQ_{ing}**	**R_{ing}**	**R_{der}**
BDE-47	1.00E-04	2.2E-02		3.0E+01	5.45E-03		7.6E+00	1.50E-02		2.1E+01
BDE-99	1.00E-04	4.5E-02		6.2E+01	9.79E-03		1.4E+01	2.24E-02		3.1E+01
BDE-153	2.00E-04	4.0E-02		5.5E+01	3.07E-03		4.3E+00	1.52E-02		2.1E+01
BDE-209	7.00E-03	5.7E-03		7.9E+00	2.93E-02		4.1E+01	3.78E-03		5.2E+00
∑HQ=HI		**1.1E-01**		**1.6E+02**	**4.76E-02**		**6.6E+01**	**5.64E-02**		7.8E+01

Table 6.16: Oral Reference Dose (RfD), Inhalation Reference Dose (RfC), Gastrointestinal Absorption Factor (GIABS) for metals

Metals	**RfD**	**RfC**	**GIABS**
V	5.00E-03	1.00E-04	2.60E-02
Cr	3.00E-03	1.00E-04	2.50E-02
Mn	1.40E-01	5.00E-05	1.00E+00
Co	3.00E-03	6.00E-06	1.00E+00
Ni	1.10E-02	1.40E-05	4.00E-02
Cu	4.00E-02	1.40E+09	1.00E+00
Zn	3.00E-01		1.00E+00
As	3.00E-04	1.50E-05	1.00E+00
Se	5.00E-03	2.00E-02	1.00E+00
Mo	5.00E-03		1.00E+00
Ag	5.00E-03		4.00E-02
Cd	1.00E-03	1.00E-05	2.50E-02
Sn	6.00E-01		1
Sb	4.00E-04	0.00E+00	1.50E-01
Ba	2.00E-01	5.00E-04	7.00E-02
Hg	3.00E-04	3.00E-04	0.07
Pb	8.50E-03	1.20E-05	
Ta	1.00E-05		1.00E+00
Fe	7.00E-01		1.00E+00
Ti		1.00E-04	1

Supplementary Table 6.17: Total HI Estimate for PBDEs and Metals for Non-Cancer Effects (Log Transformed Data)

Samples	Location	Activity	Ingestion	Inhalation	Dermal contact
Direct dust	Ibadan	Dismantling	-0.05	-6	3.73
		Repair	0.18	-6.89	3.6
Floor dust	Lagos	Dismantling	-0.48	-6.92	3.23
		Repair	-0.18	-7.17	3.18
	Ibadan	Repair	-0.16	-7.02	3.36
	Aba	Repair	-0.13	-6.85	3.74
		Dismantling	-0.16	-7.09	3.15
Roadside Dust	Lagos	Dismantling	-0.06	-6.96	3.3
	Aba	Repair	0	-6.96	3.26
Soil	Lagos	Burning	0.26	-6.92	4.18
		Dismantling	-0.08	-6.77	3.36
		Repair	-0.14	-7	3.18
	Ibadan	Burning	-0.05	-6.77	3.83
		Dismantling	-0.17	-6.96	3.38
	Aba	Burning	-0.7	-6.89	3.2
		Dismantling	-0.34	-6.96	3.6
Safe Limit			0	0	0

Supplementary Table 6.18: Hazard Quotient (HQ) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Lagos

Metals	Top Soil 0-10cm									Floor dust (control soil)						Roadside dust		
	Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites			Dismantling sites		
	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}
V	1.9E-03	4.1E-10	9.91E+01	3.9E-03	8.6E-10	2.08E+02	7.8E-04	1.7E-10	4.18E+01	2.9E-03	6.4E-10	1.56E+02	2.0E-03	4.4E-10	1.07E+02	2.7E-03	5.9E-10	1.4E+02
Cr	8.8E-03	1.2E-09	4.88E+02	1.3E-02	1.7E-09	7.33E+02	6.3E-03	8.4E-10	3.50E+02	1.0E-02	1.3E-09	5.54E+02	7.3E-03	9.7E-10	4.05E+02	8.0E-03	1.1E-09	4.4E+02
Mn	4.4E-04	5.4E-09	6.09E-01	1.9E-03	2.4E-08	2.64E+00	2.2E-04	2.8E-09	3.10E-01	1.9E-03	2.3E-08	2.59E+00	8.3E-04	1.0E-08	1.15E+00	1.2E-03	1.4E-08	1.6E+00
Co	1.9E-04	4.2E-10	2.66E-01	3.2E-04	7.1E-10	4.49E-01	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.66E-01	3.6E-04	7.9E-10	5.0E-01
Ni	6.8E-03	2.4E-08	2.35E+02	1.7E-03	6.0E-09	5.98E+01	3.5E-03	1.2E-08	1.21E+02	3.5E-03	1.2E-08	1.20E+02	9.8E-04	3.4E-09	3.39E+01	2.9E-03	1.0E-08	1.0E+02
Cu	1.2E-01	1.5E-20	1.68E+02	7.3E-03	9.2E-22	1.01E+01	2.6E-04	3.3E-23	3.67E-01	7.4E-03	9.3E-22	1.02E+01	7.9E-04	9.9E-23	1.09E+00	2.3E-03	2.9E-22	3.1E+00
Zn	4.0E-03		5.60E+00	1.0E-03		1.44E+00	3.1E-05		4.35E-02	1.7E-03		2.38E+00	4.0E-04		5.54E-01	1.2E-03		1.6E+00
As	1.1E-01	9.4E-09	1.43E+01	6.3E-03	5.6E-10	2.63E+00	4.6E-03	4.1E-10	1.92E+00	7.3E-03	6.4E-10	3.0E+00	3.2E-04	2.8E-11	1.33E-01	1.7E-02	1.5E-09	6.9E+00
Se	4.6E-04	5.1E-13	6.39E-01	1.5E-05	1.7E-14	2.13E-02	1.9E-05	2.1E-14	2.66E-02	5.0E-05	5.5E-14	6.92E-02	1.9E-05	2.1E-14	2.66E-02	4.6E-05	5.1E-14	6.4E-02
Mo	6.5E-04		9.05E-01	3.8E-05		5.33E-02	1.2E-04		1.60E-01	3.8E-05		5.33E-02	3.8E-05		5.33E-02	3.8E-05		5.3E-02
Ag	3.2E-03		1.09E+02	4.2E-04		1.46E+01	7.7E-05		2.66E+00	2.6E-03		9.19E+01	1.0E-04		3.46E+00	5.9E-04		2.1E+01
Cd	4.0E-03	1.8E-09	2.22E+00	9.8E-04	4.3E-10	5.43E-01	9.8E-04	4.3E-10	5.43E-01	9.8E-04	4.3E-10	5.43E-01	9.8E-04	4.3E-10	5.43E-01	9.8E-04	4.3E-10	5.4E-01
Sn	1.7E-03		2.42E+00	3.4E-05		4.74E-02	1.8E-06		2.49E-03	2.2E-04		3.10E-01	6.8E-05		9.41E-02	4.0E-05		5.6E-02
Sb	1.5E+00		1.37E+04	2.2E-02		2.00E+02	1.4E-03		1.33E+01	4.1E-02		3.82E+02	3.8E-03		3.55E+01	1.3E-02		1.2E+02
Ba	2.6E-03	4.7E-09	5.24E+01	4.9E-04	8.7E-10	9.75E+00	2.1E-04	3.6E-10	4.06E+00	1.4E-03	2.4E-09	2.72E+01	4.4E-04	7.7E-10	8.64E+00	9.6E-04	1.7E-09	1.9E+01
Hg	6.4E-04	2.8E-12	1.27E+01	3.1E-03	1.4E-11	6.2E+01	6.4E-04	2.8E-12	1.3E+01	2.9E-03	1.3E-11	5.8E+1	6.4E-04	2.8E-12	1.3E+01	2.3E-04	1.0E-12	4.6E+00
Pb																		
Ta	1.9E-02		2.66E+01	7.6E-01		1.06E+03	6.9E-01		9.59E+02	2.3E-01		3.20E+02	6.3E-01		8.73E+02	8.1E-01		1.1E+03
Fe	4.0E-03		5.61E+00	1.7E-02		2.38E+01	6.0E-03		8.37E+00	1.8E-02		2.51E+01	9.1E-03		1.26E+01	1.4E-02		1.9E+01
Tl		7.7E-08			1.3E-07			8.7E-08			8.0E-08			5.2E-08			7.7E-08	
∑HQ	**1.8E+00**	**1.2E-07**	**1.5E+04**	**8.4E-01**	**1.7E-07**	**2.3E+03**	**7.2E-01**	**1.0E-07**	**1.5E+03**	**3.3E-01**	**1.2E-07**	**1.7E+03**	**6.6E-01**	**6.8E-08**	**1.5E+03**	**8.7E-01**	**1.1E-07**	**2.0E+03**

Supplementary Table 6.19: Hazard Quotient (HQ) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Ibadan

	Top Soil 0-10cm						Floor dust (control soil)			Direct dust					
Metals	**Burning sites**			**Dismantling sites**			**Repair sites**			**Dismantling sites**			**Repair sites**		
	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}	HQ_{ing}	HQ_{inh}	HQ_{der}
V	4.1E-03	9.1E-10	2.21E+02	4.2E-03	9.4E-10	2.26E+02	5.0E-03	1.1E-09	2.66E+02	7.1E-02	1.6E-08	3.78E+03	8.5E-03	1.9E-09	4.55E+02
Cr	1.6E-02	2.1E-09	8.73E+02	1.3E-02	1.8E-09	7.46E+02	1.5E-02	2.0E-09	8.59E+02	1.8E-03	2.4E-10	1.02E+02	1.8E-02	2.4E-09	1.00E+03
Mn	2.0E-03	2.5E-08	2.81E+00	1.5E-03	1.9E-08	2.14E+00	2.1E-03	2.6E-08	2.88E+00	4.4E-03	5.4E-08	6.11E+00	2.2E-03	2.7E-08	3.03E+00
Co	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.66E-01	9.3E-03	2.0E-08	1.28E+01	1.9E-04	4.2E-10	2.66E-01
Ni	3.2E-03	1.1E-08	1.13E+02	2.3E-03	7.9E-09	7.87E+01	1.5E-03	5.2E-09	5.20E+01	1.1E-02	3.9E-08	3.87E+02	2.7E-03	9.4E-09	9.44E+01
Cu	1.2E-01	1.5E-20	1.70E+02	1.3E-02	1.6E-21	1.79E+01	3.1E-03	3.9E-22	4.30E+00	4.0E-04	5.1E-23	5.59E-01	3.1E-03	3.9E-22	4.27E+00
Zn	4.3E-03		5.91E+00	2.3E-03		3.25E+00	1.5E-03		2.05E+00	1.6E-04		2.17E-01	3.2E-03		4.37E+00
As	1.3E-01	1.2E-08	5.5E+01	1.3E-02	1.2E-09	5.5+00	3.2E-04	2.8E-11	1.33E-01	1.5E-03	1.4E-10	6.4E-01	6.4E-03	5.6E-10	2.66E+00
Se	2.0E-03	2.2E-12	2.77E+00	3.4E-04	3.7E-13	4.69E-01	7.7E-05	8.5E-14	1.07E-01	1.9E-05	2.1E-14	2.66E-02	6.9E-05	7.6E-14	9.59E-02
Mo	6.1E-04		8.52E-01	5.5E-04		7.67E-01	4.6E-05		6.39E-02	1.0E-04		1.38E-01	2.1E-04		2.88E-01
Ag	1.2E-03		4.26E+01	6.5E-04		2.26E+01	4.2E-04		1.46E+01	1.0E-04		3.59E+00	1.2E-03		3.99E+01
Cd	2.7E-03	1.2E-09	1.49E+00	9.8E-04	4.3E-10	5.43E-01	9.8E-04	4.3E-10	5.43E-01	9.8E-04	4.3E-10	5.43E-01	1.0E-03	4.6E-10	5.75E-01
Sn	7.8E-04		1.08E+00	7.6E-05		1.05E-01	6.2E-04		8.61E-01	9.6E-07		1.33E-03	3.4E-05		4.70E-02
Sb	5.7E-01		5.25E+03	5.0E-02		4.62E+02	1.9E-02		1.78E+02	1.4E-03		1.33E+01	4.6E-02		4.26E+02
Ba	1.8E-03	3.2E-09	3.54E+01	1.1E-03	2.0E-09	2.24E+01	9.0E-04	1.6E-09	1.78E+01	1.7E-04	3.0E-10	3.42E+00	2.0E-03	3.6E-09	3.99E+01
Hg	5.9E-03	2.6E-11	1.2E+02	1.7E-03	7.3E-12	3.3E+01	9.0E-04	4.0E-12	1.8E+01	6.4E-04	2.8E-12	1.3E+01	3.5E-03	1.5E-11	6.9E+01
Pb															
Ta	1.9E-02		2.66E+01	5.4E-01		7.46E+02	6.1E-01		8.52E+02	6.9E-01		9.59E+02	1.4E+00		1.92E+03
Fe	1.7E-02		2.39E+01	2.7E-02		3.81E+01	2.3E-02		3.24E+01	9.6E-02		1.33E+02	3.1E-02		4.36E+01
Tl		1.1E-07			7.9E-08			5.9E-08			9.0E-07			8.4E-08	
∑HQ	**9.0E-01**	**1.7E-07**	**6.8E+03**	**6.7E-01**	**1.1E-07**	**2.4E+03**	**6.9E-01**	**9.5E-08**	**2.3E+03**	**8.9E-01**	**1.0E-06**	**5.4E+03**	**1.5E+00**	**1.3E-07**	**4.0E+03**

Supplementary Table 6.20: Hazard Quotient (HQ) Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Aba

	Top Soil 0-10cm						Floor dust						Roadside dust		
Metals	**Burning sites**			**Dismantling sites**			**Dismantling sites**			**Repair sites**					
	HQ_{ing}	**HQ_{inh}**	**HQ_{der}**	**HQ_{ing}**	**HQ_{inh}**	**HQ_{der}**	**HQ_{ing}**	**HQ_{inh}**	**HQ_{der}**	**HQ_{ing}**	**HQ_{inh}**	**HQ_{der}**	**HQ_{ing}**	**HQ_{inh}**	**HQ_{der}**
V	2.2E-03	4.7E-10	1.15E+02	3.5E-03	7.8E-10	1.88E+02	2.0E-03	4.4E-10	1.07E+02	1.3E-03	2.9E-10	6.96E+01	3.2E-03	7.1E-10	1.7E+02
Cr	1.3E-02	1.7E-09	7.24E+02	2.5E-02	3.3E-09	1.40E+03	2.4E-02	3.2E-09	1.33E+03	5.4E-03	7.1E-10	2.98E+02	3.8E-03	5.1E-10	2.1E+02
Mn	1.1E-03	1.4E-08	1.59E+00	1.5E-03	1.8E-08	2.05E+00	1.8E-03	2.2E-08	2.49E+00	8.4E-04	1.0E-08	1.17E+00	7.5E-04	9.3E-09	1.0E+00
Co	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.66E-01	1.9E-04	4.2E-10	2.7E-01
Ni	3.0E-03	1.0E-08	1.04E+02	5.3E-03	1.9E-08	1.85E+02	5.2E-03	1.8E-08	1.80E+02	8.0E-04	2.8E-09	2.78E+01	5.6E-04	1.9E-09	1.9E+01
Cu	4.3E-02	5.4E-21	5.90E+01	7.6E-02	9.5E-21	1.05E+02	1.3E-01	1.6E-20	1.81E+02	1.8E-03	2.3E-22	2.54E+00	2.2E-04	2.8E-23	3.1E-01
Zn	4.5E-03		6.31E+00	7.2E-03		1.00E+01	6.9E-03		9.59E+00	6.1E-04		8.41E-01	1.5E-04		2.1E-01
As	3.1E-02	2.7E-09	1.28E+01	5.1E-02	4.5E-09	2.13E+01	9.1E-02	8.0E-09	3.78E+01	3.2E-04	2.8E-11	1.33E-01	3.2E-04	2.8E-11	1.3E-01
Se	1.9E-04	2.1E-13	2.66E-01	8.8E-04	9.7E-13	1.22E+00	3.1E-04	3.4E-13	4.26E-01	1.9E-05	2.1E-14	2.66E-02	1.9E-05	2.1E-14	2.7E-02
Mo	1.1E-03		1.49E+00	1.3E-03		1.81E+00	1.3E-03		1.86E+00	3.8E-05		5.33E-02	3.8E-05		5.3E-02
Ag	6.1E-04		2.13E+01	1.1E-03		3.86E+01	3.1E-03		1.07E+02	7.7E-05		2.66E+00	7.7E-05		2.7E+00
Cd	1.9E-04	8.5E-11	1.07E-01	9.2E-03	4.1E-09	5.11E+00	1.2E-02	5.1E-09	6.39E+00	9.8E-04	4.3E-10	5.43E-01	9.8E-04	4.3E-10	5.4E-01
Sn	5.2E-05		7.19E-02	1.5E-04		2.11E-01	4.7E-04		6.57E-01	2.2E-04		3.00E-01	3.5E-06		4.9E-03
Sb	4.7E-02		4.35E+02	1.9E-01		1.80E+03	3.7E-01		3.39E+03	9.6E-03		8.88E+01	1.1E-03		9.8E+00
Ba	1.9E-03	3.3E-09	3.70E+01	7.5E-03	1.3E-08	1.49E+02	1.9E-03	3.4E-09	3.77E+01	4.1E-04	7.3E-10	8.18E+00	3.3E-04	5.8E-10	6.5E+00
Hg	6.4E-04	2.8E-12	1.3E+01	6.4E-04	2.8E-12	1.3E+01	6.4E-04	2.8E-12	1.3E+01	6.4E-04	2.8E-12	1.3E+01	1.3E+01	5.6E-12	2.5E+01
Pb															
Ta	1.9E-02		2.66E+01	3.8E-02		5.33E+01	3.8E-02		5.33E+01	6.5E-01		9.05E+02	1.0E+00		1.4E+03
Fe	2.8E-02		3.91E+01	3.8E-02		5.33E+01	5.3E-02		7.40E+01	1.0E-02		1.43E+01	9.8E-03		1.4E+01
Tl		9.7E-08			4.4E-08			8.4E-08			6.5E-08			9.3E-08	
∑HQ	**2.0E-01**	**1.3E-07**	**1.6E+03**	**4.6E-01**	**1.1E-07**	**4.0E+03**	**7.4E-01**	**1.4E-07**	**5.5E+03**	**6.9E-01**	**8.1E-08**	**1.4E+03**	**1.0E+00**	**1.1E-07**	**1.8E+03**

Supplementary Table 6.21: Cancer Risk of BDE-209 through Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites in Lagos

PBDE	SF	Top soil									Floor dust (control soil)						Roadside dust		
		Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites			Dismantling sites		
		R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}
BDE-209	7.0E-04	4.73E-09		6.6E-06	4.0E-10		5.6E-07	2.3E-13		3.2E-10	8.1E-10		1.1E-06	1.2E-10		1.6E-07	2.6E-10		3.6E-07

Supplementary Table 6.22: Cancer Risk of BDE-209 through Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste In Ibadan

PBDE	SF	Top soil						Floor dust (control soil)			Direct dust					
		Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites		
		R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}
BDE-209	7.0E-04	1.6E-06		2.2E-03	3.5E-09	1.5E-17	4.8E-06	2.2E-06	9.5E-15	3.0E-03	8.5E-06	3.8E-14	1.2E-02	3.9E-07	1.7E-15	5.5E-04

Supplementary Table 6.23: Cancer Risk of BDE-209 through Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites and in Aba

PBDE	SF	Top soil			Floor dust (control soil)			Roadside dust		
		Burning sites			Repair sites			Repair sites		
		R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}
BDE-209	7.0E-04	2.8E-08		3.9E-05	1.4E-07	6.3E-16	2.05-04	1.9E-08	8.2E-17	2.6E-05

Supplementary Table 6.24: Cancer Risk of Metals through Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites and in Lagos

Metals				Top soil									Floor dust (control soil)						Roadside dust		
				Burning sites			Dismantling sites			Repair sites			Dismantling sites			Repair sites			Dismantling sites		
	Sf oral	IUR	GIABS	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der} =	R_{ing} =	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}
Cr	5.0E-01	8.4E-02	2.5E-02	1.3E-05	9.8E-15	4.6E-04	2.0E-05	1.5E-14	6.9E-04	9.5E-06	7.0E-15	3.3E-04	1.5E-05	1.1E-14	5.2E-04	1.1E-05	8.1E-15	3.8E-04	1.2E-05	8.9E-15	4.2E-04
Co		9.0E-03	1	0	2.3E-17			3.9E-17			2.3E-17			2.3E-17			2.3E-17			4.3E-17	
Ni		2.6E-04	4.0E-02	0	8.6E-17			2.2E-17			4.4E-17			4.4E-17			1.2E-17			3.7E-17	
As	1.5	4.3E-03	1	4.8E-05	6.1E-16	2.0E-02	2.8E-06	3.6E-17	1.2E-03	2.1E-06	2.6E-17	8.6E-04	3.3E-06	4.2E-17	1.4E-03	1.4E-07	1.8E-18	6.0E-05	7.5E-06	9.5E-17	3.1E-03
Cd		1.8E-03	2.5E-02	0	3.2E-17			7.8E-18			7.8E-18			7.8E-18			7.8E-18			7.8E-18	
Hg		3.00E-04	0.07	0	2.5E-19			1.2E-18			2.5E-19			1.2E-18			2.5E-19			9.1E-20	
Pb	8.50E-03	1.20E-05	1	2.1E-05	1.3E-16	2.9E-02	6.5E-07	4.0E-18	9.0E-04	4.0E-08	2.5E-19	5.5E-05	9.0E-07	5.6E-18	1.3E-03	1.9E-07	1.2E-18	2.6E-04	1.2E-06	7.6E-18	1.7E-03
HI				8.2E-05	1.1E-14	4.9E-02	2.3E-05	1.5E-14	2.8E-03	1.2E-05	7.1E-15	1.2E-03	1.9E-05	1.1E-14	3.1E-03	1.1E-05	8.2E-15	7.0E-04	2.1E-05	9.1E-15	5.2E-03

IUR = Inhalation Unit Risk. SF= Slope factor. GIABS = Gastrointestinal Absorption Factor

Supplementary Table 6.25: Cancer Risk of Metals through Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites and in Ibadan

Metals	Sforal	IUR	GIABS	Top soil						Floor dust (control soil)						Direct dust		
				Burning sites			Dismantling sites			Dismantling sites			Dismantling sites			Repair sites		
				R_{ing} =	R_{inh}	R_{derl}	R_{ing} =	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der} =	R_{ing}	R_{inh}	R_{der}
Cr	5.0E-01	8.4E-02	2.5E-02	2.4E-05	1.8E-14	8.2E-04	2.0E-05	1.5E-14	7.0E-04	2.3E-05	1.7E-14	8.1E-04	2.7E-06	2.0E-15	9.5E-05	2.7E-05	2.0E-14	9.4E-04
Co		9.0E-03	1		2.3E-17			2.3E-17			2.3E-17			1.1E-15			2.3E-17	
Ni		2.6E-04	4.0E-02		4.1E-17			2.9E-17			1.9E-17			1.4E-16			3.4E-17	
As	1.5	4.3E-03	1	5.9E-05	7.5E-16	2.5E-02	5.9E-06	7.5E-17	2.5E-03	1.4E-07	1.8E-18	6.0E-05	6.9E-07	8.7E-18	2.9E-04	2.9E-06	3.6E-17	1.2E-03
Cd		1.8E-03	2.5E-02		2.1E-17			7.8E-18			7.8E-18			7.8E-18			8.2E-18	
Hg		3.00E-04	0.07		2.3E-18			6.6E-19			3.6E-19			2.5E-19			1.4E-18	
Pb	8.50E-03	1.20E-05	1	7E-05	4.4E-16	9.7E-02	8.0E-06	5.0E-17	1.1E-02	3.1E-06	1.9E-17	4.3E-03	1.6E-09	1.0E-09	2.3E-06	1.5E-06	9.2E-18	2.0E-03
∑HQ=HI				**1.5E-04**	**1.9E-14**	**1.2E-01**	**3.4E-05**	**1.5E-14**	**1.4E-02**	**2.6E-05**	**1.7E-14**	**5.2E-03**	**3.4E-06**	**3.3E-15**	**3.9E-04**	**3.1E-05**	**2.0E-14**	**4.2E-03**

Supplementary Table 6.26: Cancer Risk of Metals through Ingestion, Inhalation, Dermal in Soil and Dust at various E-waste Sites and in Aba

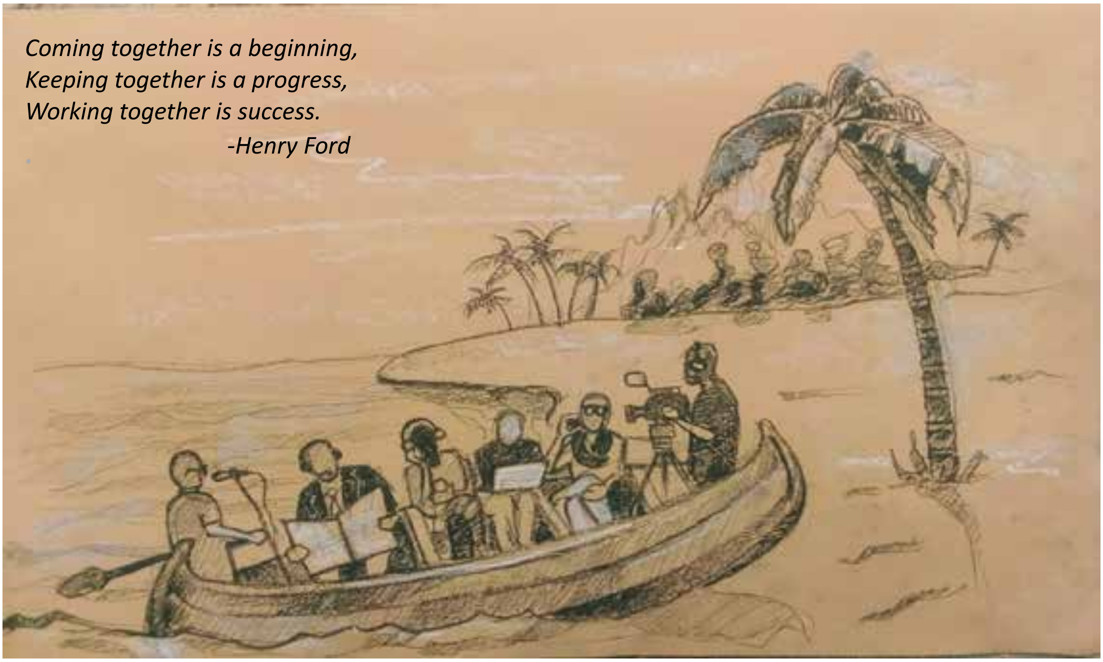
				Top soil						Floor dust (control soil)						Roadside dust		
				Burning sites			Dismantling sites			Dismantling sites			Repair sites			Repair sites		
Metals	**Sforal**	**IUR**	**GIABS**	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	R_{der}	R_{ing}	R_{inh}	$R_{der =}$	$R_{ing =}$	$R_{inh =}$	$R_{der =}$
Cr	5.0E-01	8.4E-02	2.5E-02	2.0E-05	1.5E-14	6.8E-04	3.8E-05	2.8E-14	1.3E-03	3.6E-05	2.7E-14	1.3E-03	8.1E-06	6.0E-15	2.8E-04	1.9E-03	4.3E-15	2.7E+00
Co		9.0E-03	1	0	2.3E-17			2.3E-17			2.3E-17			2.3E-17			2.3E-17	
Ni		2.6E-04	4.0E-02	0	3.8E-17			6.7E-17			6.6E-17			1.0E-17			7.0E-18	
As	1.5	4.3E-03	1	1.4E-05	1.7E-16	5.8E-03	2.3E-05	2.9E-16	9.6E-03	4.1E-05	5.2E-16	1.7E-02	1.4E-07	1.8E-18	6.0E-05	4.8E-04	1.8E-18	2.0E-01
Cd		1.8E-03	2.5E-02	0	1.5E-18			7.3E-17			9.1E-17			7.8E-18			7.8E-18	
Hg		3.00E-04	0.07	0	2.5E-19			2.5E-19			2.5E-19			2.5E-19			5.1E-19	
Pb	8.50E-03	1.20E-05	1	4.9E-06	3.1E-17	6.8E-03	7.4E-06	4.6E-06	1.0E-02	1.2E-05	7.7E-17	1.7E-02	4.9E-07	3.0E-18	6.8E-04	1.1E-07	6.9E-19	1.5E-04
∑HQ=HI				**3.8E-05**	**1.5E-14**	**1.3E-02**	**6.8E-05**	**2.9E-14**	**2.1E-02**	**8.9E-05**	**2.8E-14**	**3.5E-02**	**8.7E-06**	**6.0E-15**	**1.0E-03**	**6.0E-06**	**4.3E-15**	**4.1E-04**

Supplementary Table 6.27: Total HI Estimate for PBDEs and Metals for Cancer Risks (Log Transformed Data)

Samples	Location	Activity	Ingestion	Inhalation	Dermal contact
Direct dust	Ibadan	Dismantling	-5,47	-14,52	-3,41
		Repair	-4,51	-13,7	-2,38
Floor dust	Lagos	Dismantling	-4,72	-13,96	-2,51
		Repair	-4,96	-14,1	-3,15
	Ibadan	Repair	-4,58	-13,77	-2,28
	Aba	Dismantling	-4,05	-13,55	-1,46
		Repair	-5,06	-14,22	-3
Roadside Dust	Lagos	Dismantling	-4,68	-14,05	-2,28
	Aba	Repair	-5,22	-14,4	-3,39
Soil	Lagos	Burning	-4,09	-13,96	-1,31
		Dismantling	-4,64	-13,82	-2,55
		Repair	-4,92	-14,15	-2,92
	Ibadan	Burning	-3,82	-13,72	-0,92
		Dismantling	-4,47	-13,82	-1,85
	Aba	Burning	-4,42	-13,82	-1,89
		Dismantling	-4,17	-13,54	-1,68
Safe Limit			-6	-6	-6

Supplementary Table 6.28: Cumulative HI Estimate for PBDEs and Metals for Non-Cancer effects and Cancer Risks (Log Transformed Data)

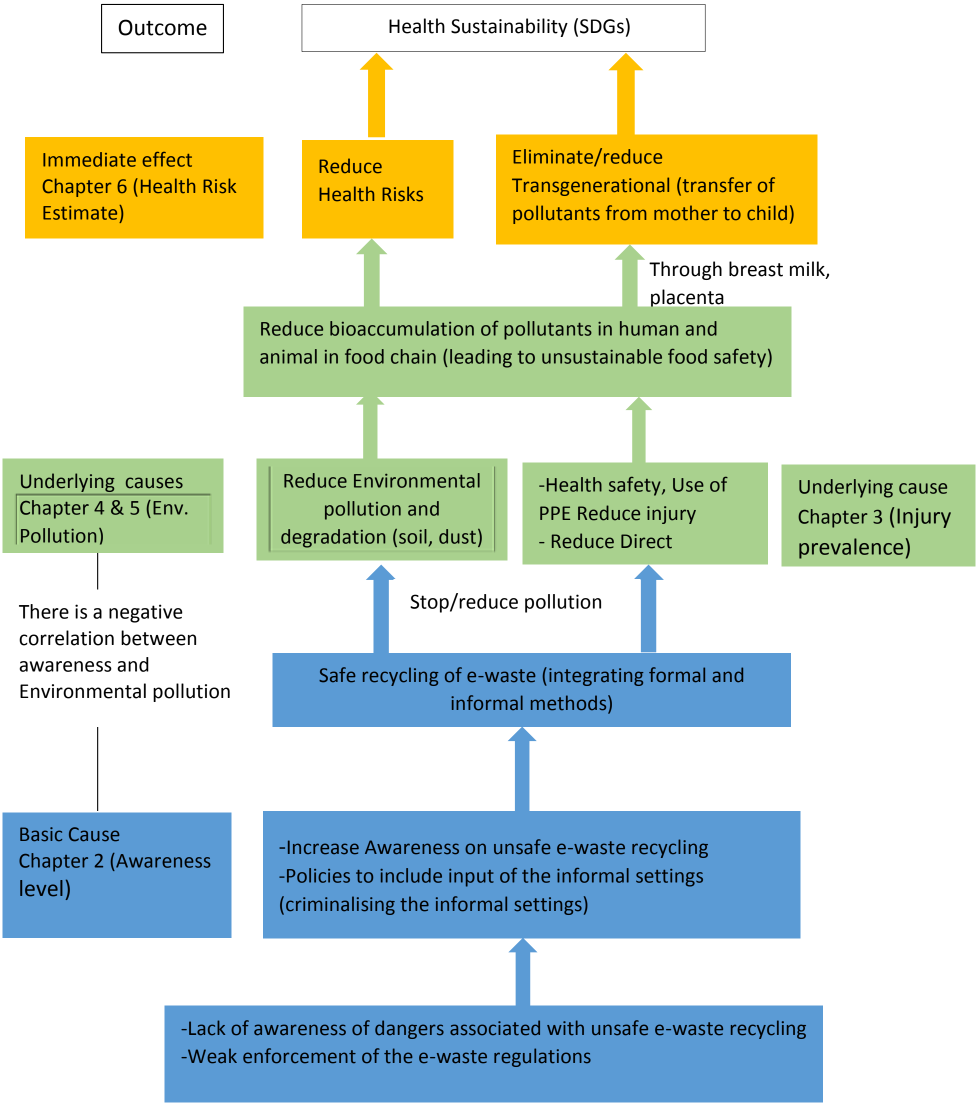
Samples	Location	Activity	Non-cancer Effects	Cancer Risks
Direct dust	Ibadan	Dismantling	3.73	-3.41
		Repair	3.6	-2.38
Floor dust	Lagos	Dismantling	3.23	-2.51
		Repair	3.18	-3.15
	Ibadan	Repair	3.36	-2.28
	Aba	Dismantling	3.74	-1.46
		Repair	3.15	-3
Roadside Dust	Lagos	Dismantling	3.3	-2.28
	Aba	Repair	3.26	-3.39
Soil	Lagos	Burning	4.18	-1.31
		Dismantling	3.36	-2.55
		Repair	3.18	-2.92
	Ibadan	Burning	3.83	-0.92
		Dismantling	3.38	-1.85
	Aba	Burning	3.2	-1.89
		Dismantling	3.6	-1.68
Safe Limit			0	-6


Coming together is a beginning,
Keeping together is a progress,
Working together is success.
-Henry Ford

Chapter 7

General Discussion

Synthesis of the Research Addressing the Impacts of Informal E-waste Recycling



7.Revisiting Research Questions and Findings

7.1 Key Findings

Across the world, electronic or electrical devices have become indispensable in our daily lives, with many people now owning multiple personal electronic devices. This has led to an exponential generation of electronic waste (e-waste) at an annual growth rate of 3–5%, which is approximately three times faster than the growth of other municipal solid waste. In 2016, 44.7 million metric tonnes (Mt) of e-waste was generated globally, and this volume of e-waste is expected to increase by 17% by 2021. Of the volume of e-waste generated, only 20% is collected and recycled formally, the remaining 80% goes undocumented (Baldé *et al*., 2017), and are simply sent to dumpsites/landfills to/in many developing countries where they are recycled informally. Informal e-waste recycling practices release hazardous substances which can have health and environmental consequences (Wong *et al.,* 2007). These practices occur more often in countries (such as Nigeria) where appropriate infrastructure for e-waste management is absent. Considering the attention on the challenges of informal e-waste recycling, there have been several international and national regulations to regulate the sector, but enforcement of these regulations is weak in developing countries.

Despite the draw backs associated with informal e-waste recycling, it creates employment and livelihood opportunities for many families and their dependents. Informal economy thrives in a context of soaring unemployment. This is a major concern in mitigating the impact of informal e-waste recycling without impeding the people's livelihood. Due to the exponential growth of e-waste generated and increasing unemployment, this thesis emphasises on the importance of tackling informal e-waste management from the perspective of providing sustainable solutions. From this perspective, one would want to ask: -

What are the existing management regulations, policies, and guidelines? Are all relevant stakeholders (e.g the e-waste workers) aware of these regulations? How are the regulations implemented? Are the e-waste workers aware of the environmental and health risks associated with informal e-waste recycling? Are the regulations and policies feasible for informal settings? Are there new strategies needed to implement and enforce the regulations and policies more appropriately in the informal settings?

Considering the potential risk of exposure to e-waste mixture chemicals ansd the associated health risks, the focus of this PhD research is on the impact of informal e-waste recycling on the health of e-waste workers and the environment. This study therefore aims to answer the following questions:

- Are e-waste workers in Nigeria aware of health risks inherent in their daily jobs and what factors influence their awareness?

- What is the prevalence and injury pattern among e-waste workers in the informal sector in Nigeria?
- What is the impact of informal electronic waste recycling on metal, concentrations in soils and dusts?
- Polybrominated Diphenyl Ethers (PBDEs) being one of the most harmful substance, what quantity of Polybrominated Diphenyl Ethers (PBDEs) are released into soils and dusts as a result of various activities at informal electronic waste recycling sites?
- Are there adverse health risks associated with exposure to PBDEs and metals at the e-waste sites?

These questions have been addressed in the preceding chapters 2-6. This study conceptualised some underlying causes contributing to informal e-waste recycling and its overall impact on health. The conceptual framework of this research is presented in chapter 1. Each chapter of this research work contributed in addressing the identified causes. The present chapter provides the research synthesis, societal and scientific implications of the findings and recommendations (figure 7.1).

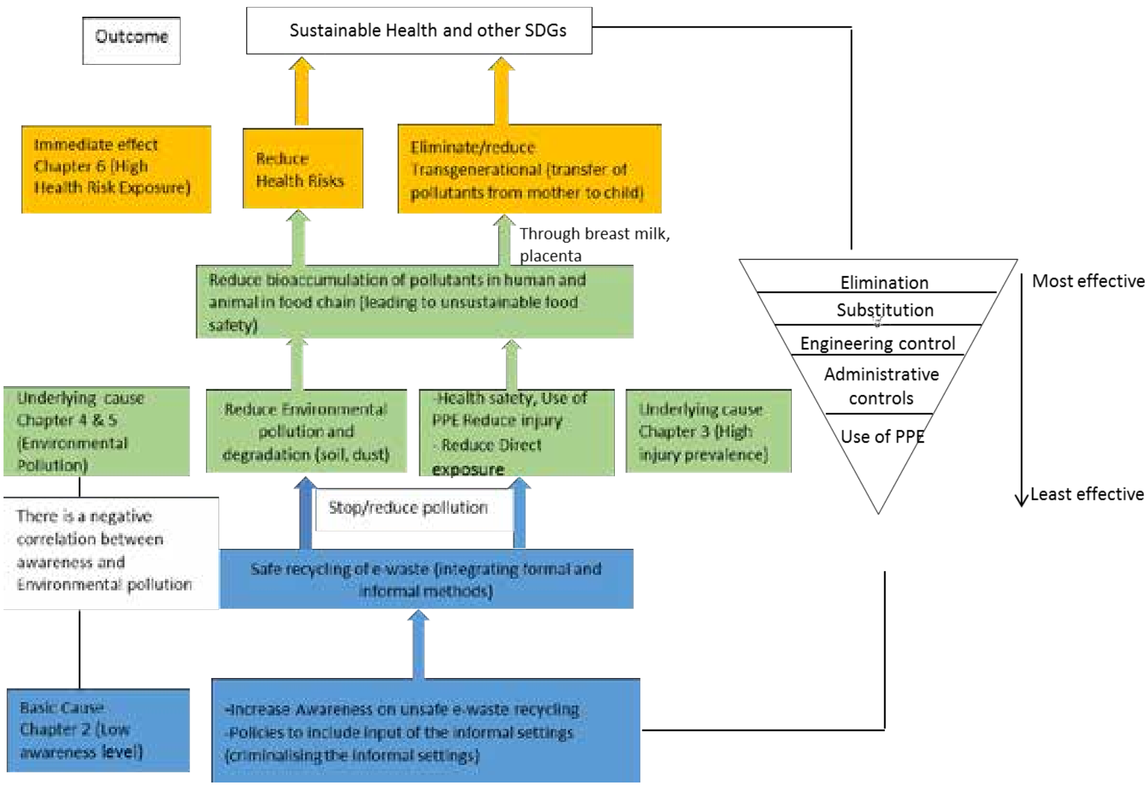


Figure 7.1: Synthesis of the Research showing the Major Outcomes and Recommendations

In addressing some of these questions, the researcher is cognizant of the fact that sustainable development involves human values, such as cultural values, equity, trust, and perceived fair relationship between the formal and the informal institutions. It is important to understand the actual operations of the informal economy, considering that this is a major source of livelihood of the people involved. Therefore the workers (e-waste workers and the control group-butchers) were interviewed. Chapter 2 unveils that the e-waste workers are not aware of the risks they are exposed to daily. The awareness level of the workers shows that informal workers often appear to underestimate or deny the health risks associated with their jobs. This could be because this job is a means of livelihood for them and they cannot escape from the risks easily. This is in accordance with the theory of Cognitive Dissonance proposed by Festinger in 1957 in which he stated that recognition of inconsistency will cause dissonance, and will motivate an individual to resolve the dissonance by either change of beliefs, change of actions, or change of perception of action (Festinger, 1957). They make statements like "*one could get sick from many other things not necessarily due to the unsafe methods of e-waste recycling*" which they practice.

Overall e-waste workers have poorer knowledge (88%), more negative attitude (74%), and more unsafe practices (58%) compared to butchers (control group) regarding the potential health risks inherent to their jobs. The health risk awareness level of the e-waste workers was significantly lower compared with their counterparts (butchers) in the same informal sector, and only 43% of the e-waste workers could mention one or more types of Personal Protective Equipment (PPE) needed for their job compared with 70% of the control group (butchers). The majority (88%) of e-waste workers were unaware that e-waste contains hazardous chemicals which could pose a risk to their health. Seventy percent did not think that the substances they are exposed to at work can pose any health risk and did not think that they could get ill from their jobs, but rather from other sources unrelated to their work or work environment. Some of them said "*one can die as a result of anything, not necessarily this job*". However, none of the groups (e-waste workers and butchers) had remarkable knowledge, attitude or best practice regarding their jobs. This confirms the statements made by Widmer *et al*., (2005), Borthakur & Sinha, (2013) and Lundgren, (2012) who claimed that most of the participants in the informal e-waste recycling sector are not aware of environmental and health risks and do not know of better practices. Only about 4% of the e-waste workers mentioned worrying about their health. The majority (51%) of the e-waste workers and 48% of the butchers reported that their major concern is finance (making more money). This shows that most workers in the informal sector work mainly for economic benefits as also confirmed by ILO (2013).

There was also a correlation between the level of knowledge and work practice. Therefore, increasing the workers' health risk knowledge may decrease risky work practices, as captured in figure 7.1. This suggests that a bottom-up approach in reducing risky practices in the informal sector may be more effective in enforcing the e-waste regulations. To ensure success of any intervention programme in the informal sector, it should be borne in mind that the approach may differ depending on the type of job performed, location, and workers' position in the business, as these were the factors that influenced the workers' awareness level. Determining the level of health risk awareness of the workers was successful despite the drawbacks encountered during the data collection in which the respondents were afraid that their responses might be used against them due to the recent stricter e-waste regulations set by the government.

Chapter 3 presents the prevalence, patterns, and factors associated with occupational injuries among e-waste workers. There was high injury prevalence of 38% and 68% in 1–2 weeks and 6 months preceding the study, respectively. These findings are in line with the findings of a qualitative study in Ghana where the e-waste workers reported high frequency of injuries and no use of PPE (Asampong *et al*., 2015, Akormedi *et al*., 2013). Our study quantified the prevalence of the injuries. Despite the high prevalence of injury, the real proportion of dismantlers that sustained an injury in the timelines studied is expected to be higher than what they actually reported, because most of the dismantlers regarded only deep cuts with blood gushing as injuries, whereas minor and blunt injuries seem normal and are even unnoticed. This observation reveals a gross level of unawareness of the occupational health risks and under-reporting of work-related injuries among informal recyclers as supported by Gutberlet & Baeder (2008). This study therefore recommends an occupational safety and health programme for the informal e-waste sector as captured in figure 7.1. Despite the high occurrence of injury, only 18% of the workers use at least one type of PPE either occasionally or most of the time. The main reasons for not using PPE were 'it is not important', 'discomfort', 'cost' and 'unavailability'. Use of PPE was associated with a higher reported occurrence of injuries. There was also a negative correlation between the number of injuries sustained and the awarenesss level. These findings suggest that use of PPE might have helped to create some awareness/consciousness of potential risks of injuries among those that use PPE, and with the right knowledge, if PPE is used appropriately, injury incidence would be reduced. The main factors associated with incidence of injury were job designation and the geographical location.

To understand if the workers are at any health risk because of chemical exposure, environmental samples were collected and analysed for chemicals present in electronics. In Chapters 4 and 5, the environmental impact of various informal e-waste recycling activities (burning, dismantling and repair) was examined in top soil and various dust samples (floor dust, roadside dust, and direct dust from inside and outside the electronics). Electronic and electrical equipment contains over 1000 different substances, some of which are hazardous elements such as lead, mercury, cadmium, arsenic, beryllium and persistent organic pollutants (including polychlorinated biphenyls and brominated flame retardants) (UNEP-DTIE, 2007). These mixtures of different substances include both chemicals present in EEE components and mixtures of chemicals released into the environment during e-waste combustion, dismantling and/or repair. These chemicals may pose significant threats to the environment and to human health given the fact that these substances persist in the environment and have a great potential to accumulate in human and animal tissue (Brigden *et al*., 2008; Asante *et al*., 2012). In the environment, soil and dust are the main receptors of direct and air-borne emissions from informal e-waste recycling. Therefore, they are the most important environmental media that can reveal the distribution and fate of contaminants present in the terrestrial environment (Leung *et al*., 2008, Ackah, 2017; Tang *et al*., 2016, Tang *et al*. 2013, Xu *et al*., 2015; Lu *et al*., 2014; Wuana & Okieimen, 2011; Banerjee, 2003).

In Chapter 4, metal concentrations (inorganic chemicals) at e-waste recycling sites (burning, dismantling, and repair) were compared to the concentrations at control sites in three study locations in Nigeria (Lagos, Ibadan, and Aba). In the three study locations, mean metal concentrations at the e-waste recycling sites exceeded the concentrations at the control sites and the Nigerian standard guideline values by factors of 100s to 1000s. Burning sites contained the highest pollution level, followed by dismantling sites, then repair sites (see figure 4.3). Our findings show that informal e-waste recycling is a major source of metal pollution in Nigeria, as captured in figure 7.1. The metal concentrations found were also higher than levels reported in earlier studies at the same locations in Nigeria, indicating that the situation is worsening. There was a negative correlation between awareness and metal concentrations at the sites, indicating that as the workers' knowledge increase, the metal pollution decreases.

Polybrominated Diphenyl Ethers (PBDEs) do not occur naturally in the environment, but traces of PBDEs were found in control sites, indicating deposits of PBDEs in places away from e-waste recycling sites (source of pollution). PBDEs are highly persistent in the environment, bioaccumulate in food chains and have a high potential for long-range environmental transport. These chemicals have been detected in humans and in increasing concentrations in various environmental matrixes. There are evidences of harmful effects in humans and wildlife, which include endocrine disruption, immunotoxicity, reproductive toxicity, effects on fetal/child development (ATSDR, 2004, Zhang *et al*., 2016, Berg *et al*., 2013, Kristen *et al*., 2013), thyroid and neurologic function (Koibuchi & Yen, 2016), and cancer (Darnerud *et al*., 2001). Due to the environmental and health concerns, PBDE have been banned in the European Union, they are voluntarily phased out in the USA since 2004 (Betts, 2008, La Guardia *et al*., 2006, EU, 2017), and are listed as POPs by the Stockholm Convention (UNEP, 2009).

PBDEs have been classified as a possible human carcinogen by the US EPA since 2004. Seventeen PBDE congeners were measured in the top soil and dust samples, as reported in chapter 5. The same pattern emerged as compared to the metal concentrations. This study showed that PBDE concentrations at the e-waste recycling sites were elevated compared to the concentrations detected at the control sites by multiple folds (figure 5.3). We found high concentrations of PBDE congeners present in electronics at the e-waste sites, with the higher molecular weight PBDEs (BDE-209, BDE-153, BDE-183) having the highest concentrations, and BDE-209 being the most abundant. The general pattern of the total PBDE ($\sum_{17}$PBDEs) distribution at the *e*-waste sites showed concentrations in this decreasing order: burning sites > dismantling sites > repair sites > control sites. This shows that burning activities contribute most to the PBDE concentrations in the environmental matrices. There was a significant difference in concentration of PBDEs among the different *e*-waste activities. This finding confirms that the type of activities at the sites influences the level of PBDEs at the sites. This study demonstrates again that crude recycling of e-waste is a significant contributor of organic pollutants in the environment, this is also shown in figure 7.1. In addition, there was a negative correlation between awareness and metal concentrations at the sites, suggesting that increasing workers' knowledge and awareness may decrease metal pollution from informal e-waste recycling.

Due to the work practices of the e-waste workers and the high concentrations of e-waste chemicals (metals and PBDEs) found at the e-waste sites, the potential health risk for the e-waste workers was estimated. Risk assessment is the process of quantitatively determining the likelihood of adverse effect resulting from exposure to hazardous substance, and the probable magnitude of adverse health effects over a specified time period. Exposure to PBDEs and metals was considered as a proxy for exposure to the complex mixture of organic and inorganic chemicals respectively as present at the e-waste recycling sites. E-waste workers are inadvertently exposed to both classes of chemicals at various informal e-waste recycling sites. In Chapter 6, the estimation of health risks due to exposure to mixture of PBDEs ($\sum_{17}$PBDE) and metals was based on the quantification of the risk level and was expressed in terms of either a cancer risk or non-cancer health effects. The estimations are commonly reported as average daily dose (ADD). Exposure to chemicals can occur via three main pathways: (a) direct inhalation of vapour or atmospheric particulates through mouth and nose; (b) dermal absorption of PBDEs in particles adhered to exposed skin; and (c) ingestion of atmospheric particulates due to their deposition/mistaken ingestion (Ferreira-Baptista and Miguel, 2005). Overall, the cumulative hazard index (PBDEs and metals) exceeded the acceptable (safe) limit for non-cancer effects and cancer risks for all exposure routes, in all locations and at all sites, with the burning sites having the highest risks . Dermal contact is the dominant route of exposure, followed by ingestion, while exposure via inhalation is negligible. This indicated that e-waste workers and other people at the e-waste sites are prone to adverse health effects. It is strongly recommend employing hierarchical control methods in the management of informal e-waste recycling without impeding livelihood. This is simplified on the conceptual frame work diagram (figure 1.1) and the synthesis on figure 7.1.

7.2 Scientific Implications

This study employed epidemiological methods of sample selection to ensure that the target groups and sites are rightly selected, adequately represented and described. Therefore, the health and environmental implications of informal e-waste recycling revealed and the recommendations in this study are applicable to similar situations in other places where of informal e-waste recycling is practiced. This study estimated the health risks the workers are exposed to, the findings are worrisome and cannot be ignored, pollution levels are high, as the e-waste workers are exposed to high health risks, and they workers are unaware of the health risks associated with their jobs. There is a need to perform additional biomonitoring studies (using blood, urine, breast milk samples) of the e-waste workers and even air sampling at the informal e-waste recycling sites, and this attention should be extended to children in the e-waste recycling vicinity. However, greater knowledge is gained if epidemiological studies are linked to the findings from toxicological studies. Toxicological models which have served as a valuable tool for analysing experimentally generated toxicity data, for predicting adverse effects in humans, and for estimating upper and lower bounds on health risks. Combining epidemiological and toxicological studies gives a more realistic description of cause and effect of the toxicants to humans. I recommend further toxicological and genetic studies to determine the real health effects even at molecular level associated with exposure to multiple chemicals through different exposure pathways which might not have been identified in this study. I also recognize that I did not identify all compounds present in the emissions at the e-waste recycling sites. There is a need for further epidemiological studies on health of the e-waste workers, other workers and residents around the e-waste sites. Furthermore, further epidemiological-toxicological studies in this area are recommended to be carried out to ensure that important associations are identified, associations are not overemphasied, and more serious health risks are not missed. In addition, it is highly likely that the evidence gained from these combined studies drive will public policies and in turn will lower exposure to health risks. It is important to note that exposure to these chemicals could be transgenerational, therefore urgent measures should be in place to mitigate exposure to these hazardous chemicals as shown in figure 7.1.

7.3 Recommendations

The findings of this study are a wake-up call on the urgent need for safety measures to be enforced in the informal e-waste recycling sector in Nigeria, and our result can be related to similar situations anywhere globally. The low health risk awarenes level, low use of PPE, high prevalence of injury among the e-waste workers, high concentrations of metal and PBDEs in the environment, and high risk of adverse health effects, give an insight into the magnitude of future environmental and health problems of uncontrolled informal e-waste recycling to both the e-waste workers and those around the e-waste sites. This also means that the impact could go beyond the present to future generations (unborn children) that are likely to inherit the health problems if appropritate actions are not taken now. The recommendations that are derived on the basis of the key outcomes of this thesis are the following:

- There is a need to implement an end-of-life product framework which is operational in developed countries such as a product take-back system and extended producer responsibility (EPR) schemes. This will reduce the quantities of e-waste informally recycled.
- There is a need to eliminate/ban risky practices such as open burning and dismantling that directly emit hazardous chemicals and cause noise pollution.
- There is a need to substitute risky practices such as burning with safer alternatives such as striping of copper wires instead of burning them, use of machines to dismantle the devices instead of manually hitting and dismantling them which consequently releases hazardous substances and causes noise pollution.
- The remains of the e-waste parts after extraction of valuable materials should be sent to landfills, instead of dumpsites.
- The primary approach to address the problems in informal e-waste sector has been command-and-control regulations that ban international trade in used electronics and e-waste and outlawing informal recycling, which punishes informal recyclers through fines and other measures. However, a major concerns about these regulations is the effectiveness of such command-and-control regulations even in countries that are more developed than Nigeria? Given the social and institutional constraints which led to weak enforcement of command-and-control policies to address informal recycling, there is a need to devise better more suited approaches to implement existing e-waste regulations. Formal institutions such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) should appreciate, understand and collaborate with the informal associations.
- Given the hostility that the informal sector has faced in the past, establishment of trust might be challenging. The enforcement agencies must not be seen to be antagonistic so as to

influence the workers in the informal sector to align with government policies. Although the informal associations are self-organizing, they can be encouraged to abide by government regulations if they perceive that they are appreciated by the enforcement agencies (National Environmetal Standards and Regulations Agency (NESREA) IN Nigeria. NESREA and the Ministry of Health can work together with the informal associations to develop effective grassroot communication methods which will improve the workers' health risk awareness. Solutions for effective enforcement of e-waste regulations are most likely to work when the workers generate the solutions themselves.

- Since the level of knowledge correlated with work practice and high exposure rate, there is a need for an urgent occupational safety and health programme suitable for the informal sector to be developed and implemented.
- The current policies -if successfully enforced- would reduce the environmental and health impacts. However, in low income countries with high formal unemployment rates, the current policies have negative trade-offs on:- the economic benefits, access to affordable used electronics, and encourages disposal of electronic devices at minor damages instead of reuse. In addition, the informal sector is extremely effective at collection, repair, reselling and dismantling electronics in developing countries.

Following these major concerns, we recommend integrating the best of informal and formal recycling methods important to mitigate environmental damages while sustaining the social benefits and the livelihood that e-waste recycling provides in developing countries. This includes: (1) Mixing the informal and formal e-waste recycling processes as already recommended by wang *et al*. (2013) and Manhart *et al.* (2011) who observed that mixed systems are sustainable, and (2) formulating and enforcing policies and regulations with inputs and considerations from the informal sector. It is important to explore alternative e-waste management strategies that are appropriate for the informal sector while preserving social and economic benefits. Sustainable improvement in the e-waste recycling sector is possible, but it also depends on the social reputation of the enforcement agences in the sector across ethinicity, business, and the willingness of enforcement agencies to appreciate and work with the all the e-waste workers in the informal e-waste recycling sector.

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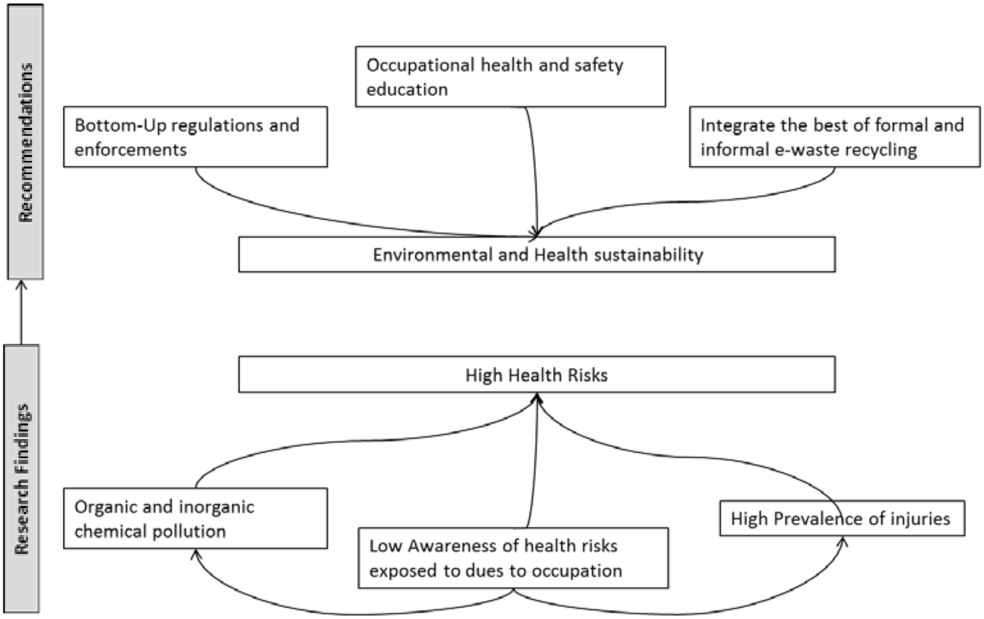
General Summary



General Summary of this Research

General Summary

Across the world, electronic or electrical devices have become indispensable in our daily lives. This growing importance and demand for electronic or electrical devices coupled with rising obsolescence due to rapid technological advancements and decreasing lifetime of electrical electronic equipment (EEE) has led to an exponential increase in the volume of EEE which are at the end- of-life, also known as electronic waste (e-waste) generated around the globe, making it one of the fastest growing municipal waste streams in the world. Globally, in 2016, 45 million metric tonnes were generated, and an estimate of 50 million metric tons will be generated in 2018. On the average the global e-waste growth is about 7%.

Only 20% of the e-waste generated are documented to be collected and properly recycled, the remaining 80% are not documented, their fate is unknown and they are informally recycled in developing countries in Asia (such as in China, India) and in Africa (such as in Ghana and Nigeria), usually with general waste without segregation. The informal e-waste recycling is on-going because these countries lack the infrastructure for e-waste recycling, there are no e-waste management legislations or weak enforcement of the legislations, and people are not aware of the dangers associated with informal or unsafe recycling of e-waste. In addition, volumes of e-waste internally generated in developing countries are increasing as more people use EEE and EEE has become indispensable in our daily lives. Although *e*-waste recycling industry is a young industry, it is rapidly growing, it has created (1) many employment opportunities; (2) affordable access to electronics and (3) parts used for repairs; (4) a continuous supply of raw materials to manufacturers; (5) conservation of natural resources and (6) conservation of energy required to manufacture new electronics from virgin resources.

Informal recycling involves labour-intensive manual dismantling, isolation of materials, open burning of plastics from electronics, heating of circuit boards, use of toxic acid baths for metal recovery as practiced in Asia, and the remaining are dumped at the open dumpsites or landfills. These unsafe activities are carried out using crude methods to recover valuable materials without or with very little technology to minimise exposure, thus allowing the emission of dangerous chemicals. Occupational safety and environmental protection are clearly not prioritized. These activities have a negative impact on the health of the workers and people around the e-waste recycling vicinity and on the environment, polluting the soil, air, dust, water. The chemicals from the e-waste can also affect the plants and animals in the environment (soil and water). The chemicals can also

bioaccumulate in the food chain and end up in fish, meat, eggs, and milk, potentially causing health problems for humans.

This research was set up to investigate the current impact of informal e-waste recycling in Nigeria. Informal e-waste recycling in Nigeria happens on a large scale, Nigeria imports the largest volume of new and used electronic and electrical equipment in Africa. About 50% of electronics used in Nigeria are imported as second-hand (used) electronics. In 2014, Nigeria generated 219 kilo tonnes. In 2016, the e-waste generated increased to 277 kilo tonnes. This is 20% increase, which is more than the global increase. And the majority of the e-waste is recycled in an unsafe manner.

Insight into the impacts of the various informal e-waste recyling activities (open burning, dismantling, repair) in developing countries is important, as it may offer opportunities for appropriate e-waste recycling management strategies suited for low resource settings to reduce the environmental and health effects of unsafe e-waste recycling. Currently, some developing countries that recycle *e*-waste in large quantity have *e*-waste legislations but enforcement of the legislations are weak such as in Nigeria. Nigeria is a signatory to international e-waste treaties and also has its own national regulations, policies and guidlines, but the enforcement is weak. This gave rise to the questions addressed in this research: Are the e-waste workers aware of these legistlations and policies? Are e-waste workers aware of the dangers associated with their daily jobs? Do they know that their jobs affect their health and the environment as they struggle for livelihood for themselves and their families? Nigerians are happy people who also love quality life, but why are people engaged in health risky jobs? Is the environment contaminated as a result of e-waste recycling? Are the workers exposed to adverse health risks?

Chapter 2 of this thesis unveils the awareness level of the workers, showing that informal workers often underestimate the health risks associated with their jobs. The majority (88%) of e-waste workers are unaware that e-waste contains hazardous chemicals which could pose a risk to their health. Health risk awareness level of the e-waste workers were significantly lower compared with their counterparts (butchers) in the same informal sector. Compared to their counterparts, the *e*-waste workers had poorer knowledge (88%), more negative attitudes (74%), and more unsafe practices (58%) regarding the potential health risks inherent in their jobs. The majority (51%) of e-waste workers are more concerned about making more money, and less about their health. The major factors that influenced workers' awareness level were type of job performed, location, and workers' position in the business.

Chapter 3 reveals the injury prevalence, patterns and factors associated with occupational injuries among e-waste workers. There was a high injury prevalence of 38% (dismantlers 25% and repairers 13%) and 68% (dismantlers 37% and repairers 31%) in 1–2 weeks and 6 months preceding the study, respectively. Despite the high occurrence of injury, only 18% of the workers use any personal protective equipment (PPE) either occasionally or most of the time. The main reasons for not using PPE were 'perceived unimportant, discomfort, cost and unavailability.

Chapter 4 and 5 reported on the environmental impact of various informal e-waste recycling activities (burning, dismantling and repair) on the environment (in top soil and various dust samples including floor dust, roadside dust, and direct dust from inside and outside the electronics). Electronic and electrical equipment contains over 1000 different substances, some of which are hazardous elements such as lead, mercury, cadmium, arsenic, beryllium and persistent organic pollutants such as Polybrominated Diphenyl Ethers (PBDEs). These mixtures of different substances are released into the environment during informal e-waste recycling which may consequently pose significant threats on the environment and human health. We found very high concentrations of toxic metal (chapter 4) and PBDEs (chapter 5) at e-waste recycling sites which exceeded the concentrations at the control sites and the Nigerian standard guideline values by 100s to 1000s times. Burning sites showed the highest pollution level, followed by dismantling sites, and then repair sites (burning > dismantling > repair > control sites). Our findings show that informal e-waste recycling is a major source of metal pollution in Nigeria.

We went further in chapter 6 to estimate the likelihood of adverse health effects (non-cancer and cancer risks) resulting from exposure of *e*-waste workers to metals and PBDEs over a specified time period. Exposure to e-waste chemicals (PBDEs and metals) can occur via three main pathways: (a) direct inhalation of vapour or atmospheric particulates through mouth and nose; (b) dermal absorption of PBDEs in particles adhered to exposed skin; and (c) ingestion of atmospheric particulates due to their deposition/mistaken ingestion. The exposure risk was in the followng order: dermal > ingestion> inhalaltion. E-waste workers are exposed to potential adverse health effects via dermal contact and ingestions of contaminated top soils and dust at all the e-waste recycling sites in all the locations. Dermal contact is the dominant route of exposure. This effect is hightened because the e-waste workers do not use adequate PPE at work, and they are not aware of the health risks associated wit their daily jobs.

Cognisant of the urgent need for safer e-waste recycling, I recommend more effective strategies to implement the e-waste regulations and policies:

1. Collaboration between enforcement agencies and informal sector associations during formulation of the regulations to ensure inputs from the informal e-waste workers are considered.
2. Regulations should not impede the workers' livelihood, as this will encourage the workers to cooporate with the government and enforcement agencies
3. Health and safety education of the e-waste workers on the dangers associated with crude e-waste recycling, and enforced use of PPE
4. Enforce the elimination of open burning as an e-waste recycling activity
5. Enforce alternatives to burning activities.
6. Integrate the best of informal and formal recycling methods to mitigate environmental damage while sustaining the social benefits and livelihood that e-waste recyling provides
7. Further toxicological and epidemiological studies on the e-waste workers and their families

Samenvatting

Over de hele wereld zijn elektronische of elektrische apparaten onmisbaar geworden in ons dagelijks leven. Dit groeiende belang en de vraag naar elektronische of elektrische apparaten in combinatie met toenemende veroudering als gevolg van snelle technologische ontwikkelingen en een afnemende levensduur van elektrische elektronische apparatuur (EEA) heeft geleid tot een exponentiële toename van het aantal EEA dat aan het einde van zijn levensduur is, ook bekend als elektronisch afval (e-waste) dat over de hele wereld wordt gegenereerd, waardoor het een van de snelst groeiende stedelijke afvalstromen in de wereld is. Wereldwijd werd in 2016 45 miljoen metrische ton gegenereerd en in 2018 wordt een schatting van 50 miljoen ton gegenereerd. Wereldwijd werd in 2016 45 miljoen metrische ton gegenereerd en in 2018 wordt een schatting van 50 miljoen ton gegenereerd. Gemiddeld is de wereldwijde e-waste-groei ongeveer 7%.

Slechts 20% van het geproduceerde e-waste is gedocumenteerd om te worden verzameld en gerecycled via formele weg. De overige 80% zijn niet gedocumenteerd, daarmee is het lot onbekend en is het meest waarschijnlijke een informeel recycle traject in ontwikkelingslanden in Azië (zoals in China, India) en in Afrika (zoals in Ghana en Nigeria), meestal gemengd met algemeen afval zonder segregatie. De informele recyclage van e-waste is aan de gang omdat deze landen niet over de infrastructuur voor e-waste recycling beschikken, er geen wetgevingen inzake elektronisch afvalbeheer zijn of zwakke handhaving van de wetgevingen. Daarnaast zijn de mensen zich niet bewust zijn van de gevaren van informeel of onveilig zijn recycling van e-waste. Daarnaast nemen de hoeveelheden intern elektronisch gegenereerd afval in ontwikkelingslanden toe naarmate meer mensen EEE en EEA gebruiken omdat het onmisbaar is geworden in ons dagelijks leven. Hoewel de e-waste-recyclingindustrie een jonge industrie is, groeit deze snel, heeft ze (1) veel werkgelegenheidskansen gecreëerd; (2) betaalbare toegang tot elektronica en (3) onderdelen gebruikt voor reparaties; (4) een continue aanvoer van grondstoffen naar fabrikanten; (5) behoud van natuurlijke hulpbronnen en (6) behoud van energie benodigd voor het vervaardigen van nieuwe elektronica uit ongebruikte hulpbronnen.

Informele recycling omvat arbeidsintensieve handmatige demontage, isolatie van materialen, open verbranding van kunststoffen uit elektronica, verwarming van printplaten, gebruik van baden met toxisch zuur voor metaalherwinning zoals toegepast in Azië, en de overige worden gedumpt bij de open stortplaatsen of stortplaatsen. Deze onveilige activiteiten worden uitgevoerd met behulp van

ruwe methoden om waardevolle materialen terug te winnen zonder of met zeer weinig technologie om de blootstelling te minimaliseren, waardoor de uitstoot van gevaarlijke chemicaliën mogelijk wordt. Arbeidsveiligheid en milieubescherming hebben duidelijk geen prioriteit. Deze activiteiten hebben een negatief effect op de gezondheid van de werknemers en mensen rond de omgeving van recycling van e-afval en op het milieu, waardoor de bodem, lucht, stof en water worden vervuild. De chemicaliën van het elektronisch afval kunnen ook van invloed zijn op de planten en dieren in de omgeving (bodem en water). De chemicaliën kunnen ook bioaccumuleren in de voedselketen en terechtkomen in vis, vlees, eieren en melk, wat mogelijk gezondheidsproblemen kan veroorzaken bij de mens.

In dit proefschrift staan onderzoeksvragen opgesteld aan de hand waarvan de huidige impact van informele recycling van e-waste in Nigeria is onderzocht. Informele recycling van e-wate in Nigeria gebeurt op grote schaal, Nigeria importeert het grootste volume van nieuwe en gebruikte elektronische en elektrische apparatuur in Afrika. Ongeveer 50% van de elektronica die in Nigeria wordt gebruikt, wordt geïmporteerd als tweedehands (gebruikte) elektronica. In 2014 genereerde Nigeria 219 kiloton. In 2016 steeg het gegenereerde e-afval tot 277 kiloton. Dit is een toename van 20%, wat meer is dan de wereldwijde stijging. En het merendeel van het e-waste wordt op een onveilige manier gerecycled.

Inzicht in de impact van de verschillende informele recyling-activiteiten van e-waste (openbranden, ontmantelen, repareren) in ontwikkelingslanden is belangrijk, omdat het mogelijkheden kan bieden voor geschikte beheerstrategieën voor e-waste recycling die geschikt zijn voor lage hulpbronnen om de milieu- en gezondheidseffecten van onveilige recycling van e-waste. Op dit moment hebben sommige ontwikkelingslanden die e-waste in grote hoeveelheden recyclen wetgeving inzake elektronisch afval, maar de handhaving van de wetgeving is zwak, zoals ook in Nigeria. Nigeria is een ondertekenaar van internationale e-waste-verdragen en heeft ook zijn eigen nationale regelgeving, beleid en richtlijnen, maar ook hiervoor geldt dat de handhaving zwak is. Dit gaf aanleiding tot de vragen die in dit onderzoek worden behandeld: zijn de e-waste werknemers op de hoogte van deze wetgeving en beleid? Zijn medewerkers van e-waste zich bewust van de gevaren van hun dagelijkse werk? Weten ze dat hun banen van invloed zijn op hun gezondheid en het milieu terwijl ze worstelen om in hun levensonderhoud te voorzien voor zichzelf en hun gezinnen? Nigerianen zijn gelukkige mensen die ook van kwaliteit leven houden, maar waarom werken deze mensen in banen die hun gezondheid risico's met zich mee brengen? Is de omgeving vervuild als gevolg van recycling van e-waste? Zijn de werknemers blootgesteld aan ongunstige gezondheidsrisico's?

Hoofdstuk 2 van dit proefschrift onthult het bewustzijnsniveau van de werknemers, waaruit blijkt dat informele werknemers vaak de gezondheidsrisico's van hun werk onderschatten. De meerderheid (88%) van de werknemers van e-waste weten niet dat e-waste gevaarlijke chemische stoffen bevat die een risico voor hun gezondheid kunnen vormen. Het gezondheidsrisicobewustzijn van de e-waste-werknemers was aanzienlijk lager in vergelijking met slagers (een beroepsgroep die als controle is gebruikt) in dezelfde informele sector. Vergeleken met hun beroeps-tegenhangers hadden de e-waste-werknemers slechtere kennis (88%), meer negatieve attitudes (74%) en meer onveilige praktijken (58%) met betrekking tot de potentiële gezondheidsrisico's die inherent zijn aan hun baan. De meerderheid (51%) van de e-waste-werknemers maakt zich meer zorgen over geld verdienen en minder over hun gezondheid. De belangrijkste factoren die het bewustzijnsniveau van werknemers beïnvloedden, waren het type uitgevoerde functie binnen de e-waste recycling, de locatie en de positie van de werknemers in het bedrijf.

Resultaten uit Hoofdstuk 3 tonen de prevalentie van letsels, patronen en factoren die verband houden met beroepsletsel bij medewerkers van e-waste. Er was een hoge prevalentie van letsel van 38% (ontmantelaars 25% en reparateurs 13%) en 68% (ontmantelaars 37% en reparateurs 31%) in respectievelijk 1-2 weken en 6 maanden voorafgaand aan het onderzoek. Ondanks het hoge voorkomen van letsel, gebruikt slechts 18% van de werknemers af en toe of meestal persoonlijke beschermingsmiddelen. De belangrijkste redenen om ze niet te gebruiken, waren 'onbelangrijk waargenomen, ongemak, kosten en het niet beschikbaarheid zijn van de middelen.

Hoofdstuk 4 en 5 staan resultaten gerapporteerd over de milieueffecten van verschillende informele e-waste recyclingsactiviteiten (verbranding, demontage en reparatie) op het milieu (in de toplaag van de bodem en verschillende stofstalen waaronder vloerstof, stof langs de weg en direct stof van binnen en buiten de elektronica). Elektronische en elektrische apparatuur bevat meer dan 1000 verschillende stoffen, waarvan sommige gevaarlijke elementen zijn zoals lood, kwik, cadmium, arsenicum, beryllium en persistente organische verontreinigende stoffen zoals polybroomdifenyl-ethers (PBDE's). Deze mengsels van verschillende stoffen komen vrij in het milieu tijdens informele recycling van e-afvalstoffen, die bijgevolg een aanzienlijke bedreiging kunnen vormen voor het milieu en de menselijke gezondheid. We vonden zeer hoge concentraties metalen (hoofdstuk 4) en PBDE's (hoofdstuk 5) op e-waste recycling locaties die de concentraties op de controlestations en de Nigeriaanse standaardrichtlijnwaarden met 100s tot 1000s keer overschreden. Waar het e-waste verband werd, daar werden het hoogste verontreinigingsniveau gevonden, gevolgd door ontmantelingslocaties en vervolgens reparatiesites (open branden> ontmanteling> reparatie> controlesites). Onze bevindingen tonen aan dat informele recycling van e-waste een belangrijke bron is van metaalverontreiniging en van PBDE’s in Nigeria.

We gingen verder in hoofdstuk 6 om de waarschijnlijkheid van nadelige gezondheidseffecten (niet-kanker- en kankerrisico's) als gevolg van blootstelling van medewerkers van e-waste aan metalen en PBDE's in een bepaalde periode te schatten. Blootstelling aan e-waste stoffen (PBDE's en metalen) kan via drie routes plaatsvinden: (a) directe inademing van damp of atmosferische deeltjes door mond en neus; (b) huidabsorptie van PBDE's in deeltjes die aan blootgestelde huid zijn gehecht; en (c) opname van atmosferische deeltjes als gevolg van hun afzetting / verkeerde inname. Het blootstellingsrisico werd: dermaal> ingestion> inhalation. Werknemers in e-waste worden blootgesteld aan mogelijke nadelige gezondheidseffecten via contact met de huid en inname van besmette toplagen van de bodem en stof op alle e-waste recyclinglocaties op alle locaties. Huidcontact is de dominante blootstellingsroute. Dit effect wordt versterkt doordat de e-waste-werknemers geen adequate PBM op het werk gebruiken.

Gezien de dringende behoefte aan veiliger recycling van e-afval, beveel ik op basis van het onderzoek in mijn proefschrift, effectievere strategieën aan om de voorschriften en het beleid inzake e-waste te implementeren:

1. Samenwerking tussen handhavingsinstanties en informele sectorverenigingen bij het formuleren van de voorschriften om ervoor te zorgen dat de input van de informele e-waste-werknemers in overweging wordt genomen.

2. Verordeningen mogen het levensonderhoud van de werknemers niet belemmeren, omdat dit de werknemers aanleiding kan zijn dat samenwerking met de regering en handhavingsinstanties stagneert.

3. Gezondheids- en veiligheidseducatie van de e-waste-werknemers over de gevaren van ruwe e-waste-recycling en afgedwongen gebruik van persoonlijke beschermingsmiddelen (PBM)

4. Verbied het open verbranden als een e-waste recyclingactiviteit

5. Dwing alternatieven voor open verbrandingsactiviteiten af.

6. Integreer het beste van informele en formele recyclingmethoden om milieuschade te beperken en tegelijkertijd de sociale voordelen en middelen van bestaan te behouden die e-waste recyling bieden

7. Voer meer (eco)toxicologisch en epidermiologische studies uit naar de omgeving, de werknemers in de e-waste en hun gezinnen.

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Curriculum Vitae

Chimere May Ohajinwa is driven by a vision of sustainable development in low resource settings whose people are healthy, happy, and empowered. She believes that achieving sustainable development does not necessarily require reinventing the wheel or rocket science, rather already existing means can be strengthened. Her desire to see a positive impact in society motivated her to work on various development-related projects with local and international not-for-profit organisations for over 7 years before embarking on her PhD programe at Leiden University. These works have exposed Chimere to experience the workings of the "formal and informal", "rural and urban", and "multicultural" settings, which she enjoys.

Her PhD research titled "*Environmental and Health impacts of informal electronic waste recycling*" stems from the passion to make a positive difference, and the concerns of potential environmental and health impact of increasing volumes of e-waste which is recycled informally in the urban cities in developing countries.

She attended Community Girls' Secondary School, Umungasi, Aba, did excellently well in the West African Certificate Examinations (WACE) for undergraduate studies in 1996. She holds a Bachelor's of Science in Applied Biochemistry from Nnamdi Azikiwe University in 2002 and a Masters of Public Health (Environmental Health) from the University of Ibadan, Nigeria in 2009. In 2014, she was offered a scholarship by the Netherlands Fellowship Programme (NFP) to pursue a PhD programme in Environmental Sciences at Leiden University, Netherlands. During her PhD programme, she had the opportunity of disseminating the findings of her research through several scientific publications in peer-reviewed journals and presentations at international scientific meetings.

Chimere had enjoyable moments in the Netherlands. Conducting scientific researches which has immediate application and positive impact is one of the best jobs in the world. Therefore, Chimere hopes to still be involved in research and development-related programmes that impact policies and regulations. She enjoys travelling, reading, writing, history & culture, cooking, and walking in the woods. www.linkedin.com/in/chimere-ohajinwa/

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UI/UCH EC Registration Number: **NHREC/05/01/2008a**

NOTICE OF FULL APPROVAL AFTER FULL COMMITTEE REVIEW

Re: Health Impacts of Exposure to new Persistent Organic Pollutants (POPs) from e-waste recycling among e-waste workers in the informal sector in Nigeria

UI/UCH Ethics Committee assigned number: UI/EC/15/0096

Name of Principal Investigator: **Chimere M. Ohajinwa**

Address of Principal Investigator: Institute of Environmental Sciences, Leiden University, Netherlands

Date of receipt of valid application: 30/03/2015

Date of meeting when final determination on ethical approval was made: **N/A**

This is to inform you that the research described in the submitted protocol, the consent forms, and other participant information materials have been reviewed and *given full approval by the UI/UCH Ethics Committee.*

This approval dates from **27/04/2015 to 26/04/2016.** If there is delay in starting the research, please inform the UI/UCH Ethics Committee so that the dates of approval can be adjusted accordingly. Note that no participant accrual or activity related to this research may be conducted outside of these dates. *All informed consent forms used in this study must carry the* UI/UCH EC *assigned number and duration of* UI/UCH EC *approval of the study.* It is expected that you submit your annual report as well as an annual request for the project renewal to the UI/UCH EC early in order to obtain renewal of your approval to avoid disruption of your research.

The National Code for Health Research Ethics requires you to comply with all institutional guidelines, rules and regulations and with the tenets of the Code including ensuring that all adverse events are reported promptly to the UI/UCH EC. *No changes are permitted in the research without prior approval by the* UI/UCH EC *except in circumstances outlined in the Code. The* UI/UCH EC *reserves the right to conduct compliance visit to your research site without previous notification.*

UI/UCH EC APPROVED

28/4/2015

Professor Catherine O. Falade
Director, IAMRAT
Chairman, UI/UCH Ethics Committee
E-mail: uiuchirc@yahoo.com

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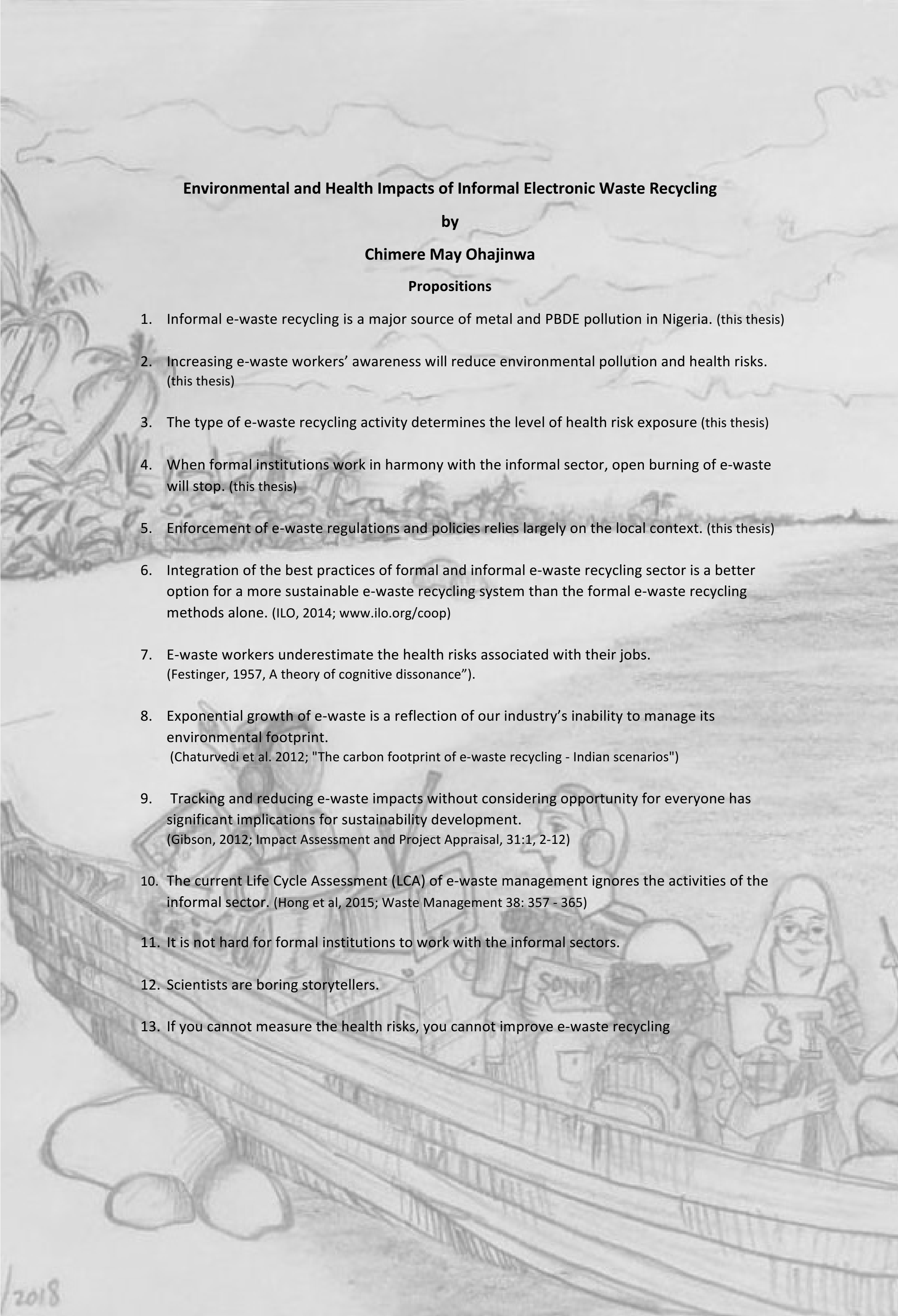

Environmental and Health Impacts of Informal Electronic Waste Recycling

by

Chimere May Ohajinwa

Propositions

1. Informal e-waste recycling is a major source of metal and PBDE pollution in Nigeria. (this thesis)

2. Increasing e-waste workers' awareness will reduce environmental pollution and health risks. (this thesis)

3. The type of e-waste recycling activity determines the level of health risk exposure (this thesis)

4. When formal institutions work in harmony with the informal sector, open burning of e-waste will stop. (this thesis)

5. Enforcement of e-waste regulations and policies relies largely on the local context. (this thesis)

6. Integration of the best practices of formal and informal e-waste recycling sector is a better option for a more sustainable e-waste recycling system than the formal e-waste recycling methods alone. (ILO, 2014; www.ilo.org/coop)

7. E-waste workers underestimate the health risks associated with their jobs. (Festinger, 1957, A theory of cognitive dissonance").

8. Exponential growth of e-waste is a reflection of our industry's inability to manage its environmental footprint. (Chaturvedi et al. 2012; "The carbon footprint of e-waste recycling - Indian scenarios")

9. Tracking and reducing e-waste impacts without considering opportunity for everyone has significant implications for sustainability development. (Gibson, 2012; Impact Assessment and Project Appraisal, 31:1, 2-12)

10. The current Life Cycle Assessment (LCA) of e-waste management ignores the activities of the informal sector. (Hong et al, 2015; Waste Management 38: 357 - 365)

11. It is not hard for formal institutions to work with the informal sectors.

12. Scientists are boring storytellers.

13. If you cannot measure the health risks, you cannot improve e-waste recycling