Article details

Impact of informal electronic waste recycling on metal concentrations in soils and dusts

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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 100 s to 1000 s 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.

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 have 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; Balde 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(Balde 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 (Balde 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., 2016a). 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

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sound management of *e*-waste, lax environmental laws/regulations, and weak enforcement of existing laws/regulations (Terada, 2012; Strategic Approach to international Chemicals Management 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 (Leung et al., 2008). Moreover, dust is a good indicator for metal levels in the atmosphere (Ackah, 2017; Tang et al., 2015, 2013; Xu et al., 2015; Lu et al., 2014; 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.

2. Methods

2.1. Study locations and sites

The study was conducted in three study locations (Ibadan, Lagos, and Aba) in Nigeria. (Fig. 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 and 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 center 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.

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 m 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 analyzed. 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. Fig. 2 presents a schematic diagram of the sample collection from the various e-waste sites in the three study locations.

2.3. Sample collection and preparation

For soil sampling, each site was divided into grids of about 10 m 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 aluminium 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 analyzed. The samples consisted of 29 top soil (0–10 cm depth), 32 floor dust, 16 roadside dust, and 5 direct dust samples from electronics.

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 (3 h at 100 °C) at 550 °C for 5 h (Pansu and 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 3 g 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.

2.5. Data analyses

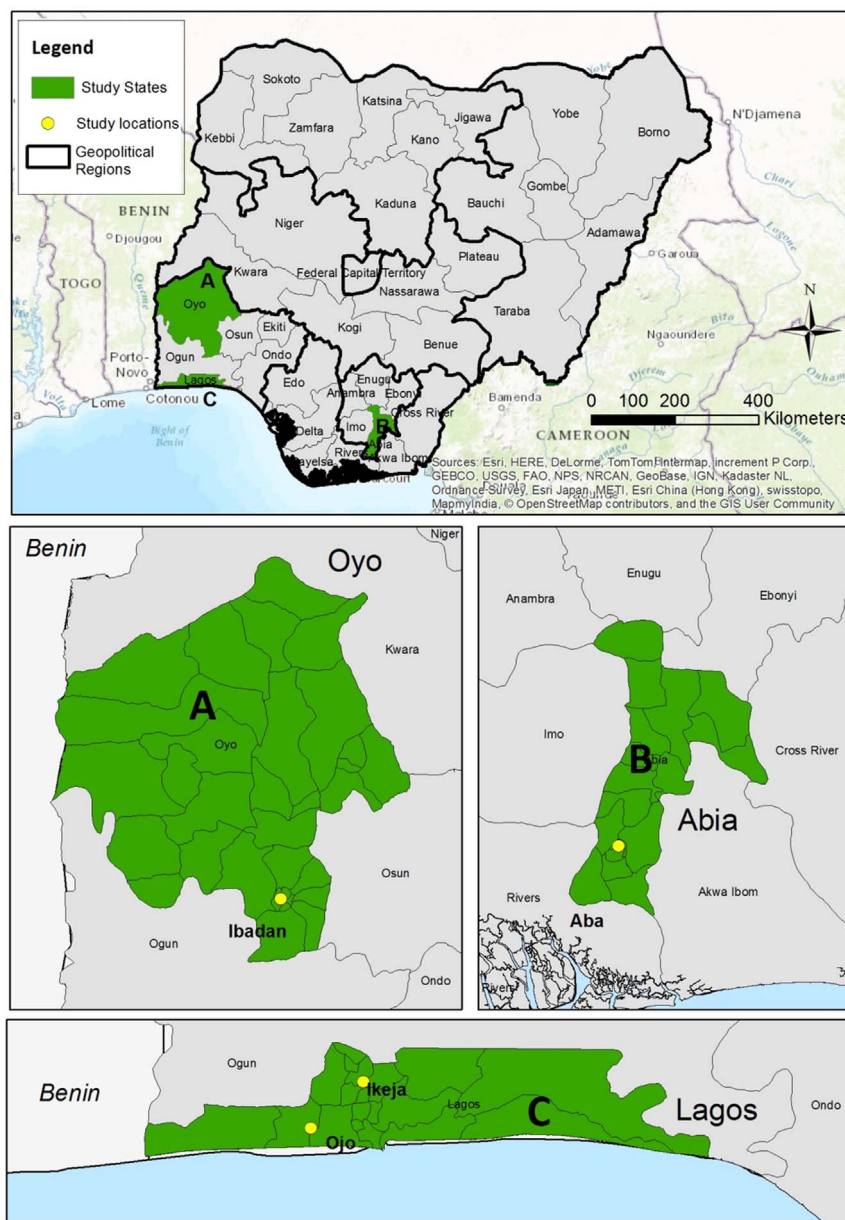In this paper, we considered twenty-two metals Ag, As, Ba, Cd, Cr,

Fig. 1. Map of Nigeria showing the study locations.

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 (Ministerie van Volkshuisvesting Ruimtelijke Ordening en Milieubeheer 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 et al., 1980). The PLI gives the public and policymakers 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
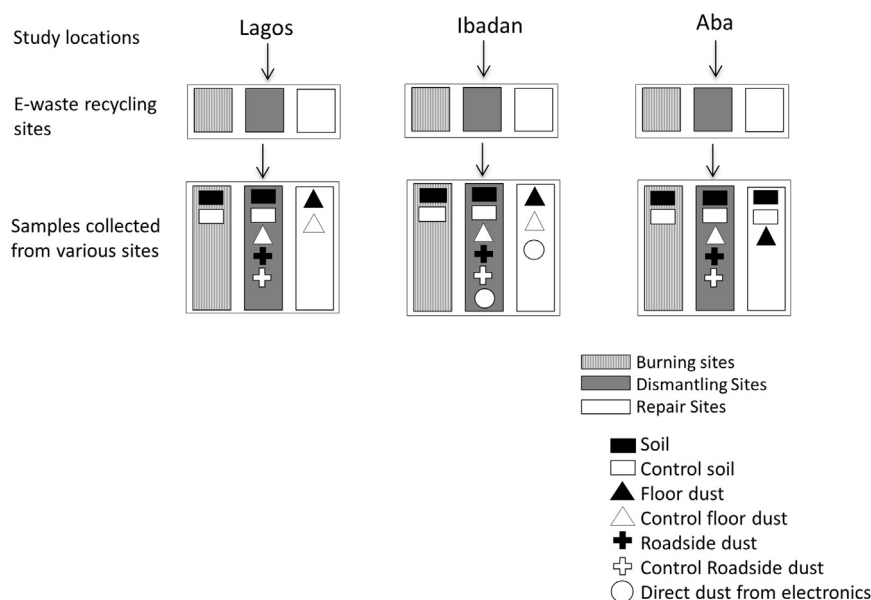
Fig. 2. Schematic flow diagram of sample collection in the study locations.

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 Fig. 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.

3. Results

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 S1. The pH for top soils ranged from 1.9 to 9.0, floor dusts 7.6–9.7, roadside dust sites 7.1–9.0, and direct dust from electronics 7.2–9.2. 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 1.1–22.3%, roadside dust 0.5–6.24%, and direct dust from electronics 4.2–22.4. 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 and Okeke, 2013).

3.2. Descriptive statistics of the metals

Supplementary Tables S2-S4 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 Fig. 3). The PLI for direct dust from electronics showed dismantling sites > repair sites (see Fig. 3). These patterns show that metal concentrations are related to the activities at the sites.

3.3. Factors that influence the metal concentrations in the environmental media

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 Fig. 4. There was a main effect
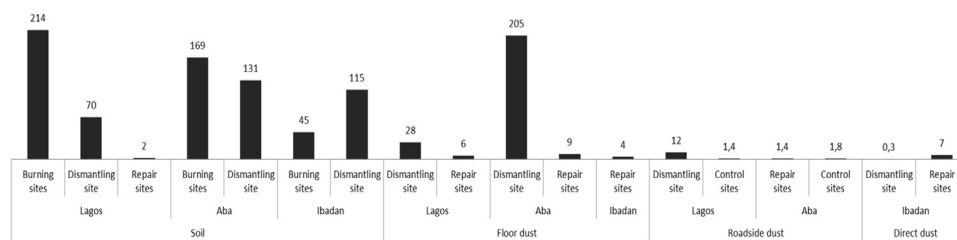
Fig. 3. Pollution Load Index of soil and dust from e-waste recycling sites.

(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 Fig. 4. Supplementary Table S5 and supplementary Fig. S1 present in detail the metals concentrations in top soil that differed significantly across the activity sites.

3.3.2. Assessment of the floor 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 (Fig. 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 metals depend on location and activities on the sites. Supplementary Table S6 and Supplementary Fig. S2a and b 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.

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, (Fig. 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 S7).

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 (Fig. 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 S7) (Fig. 8).

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 S8.
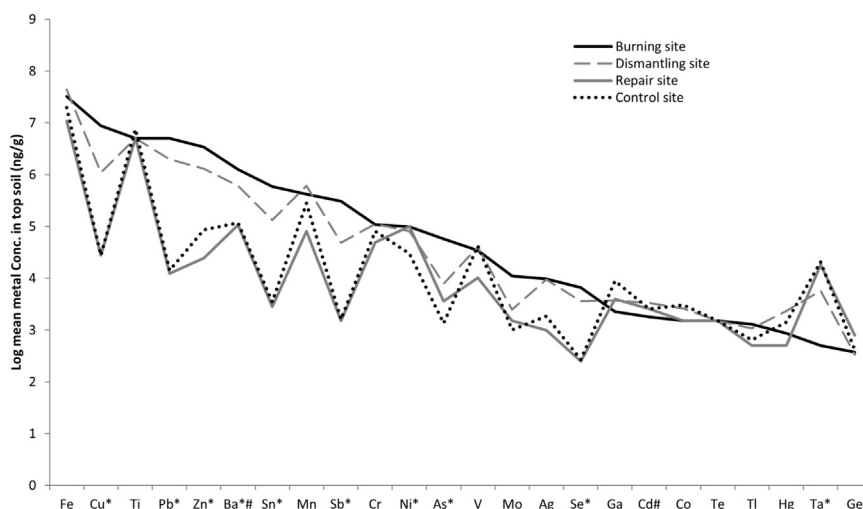

Fig. 4. Metal concentration in decreasing order in top soils across the sites. The metals influenced by activity at the sites are indicated with*, and interaction of activity and location with #.
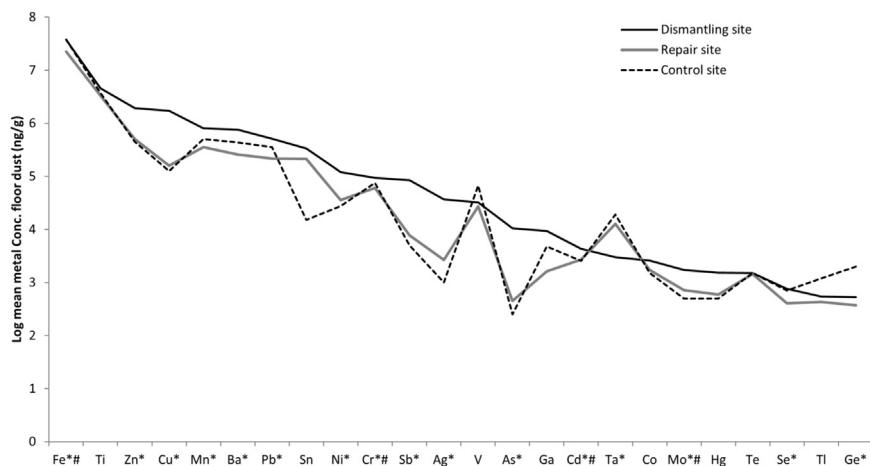
Fig. 5. Metal concentrations in floor dust across the sites. The metals influenced by activity are indicated with*, and interaction of activity and location with #.

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 S9 and S10 for Lagos and Aba, respectively).

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 (Science Communication Unit (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 al., 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 kg tonnes in 2014. (Baldé et al., 2015), to 277 kg tonnes in 2016 (Balde et al., 2017). The majority of the e-waste is recycled in an

Fig. 6. Metal concentrations in roadside dust across the activity sites. Metal concentrations with significant difference are indicated with *.
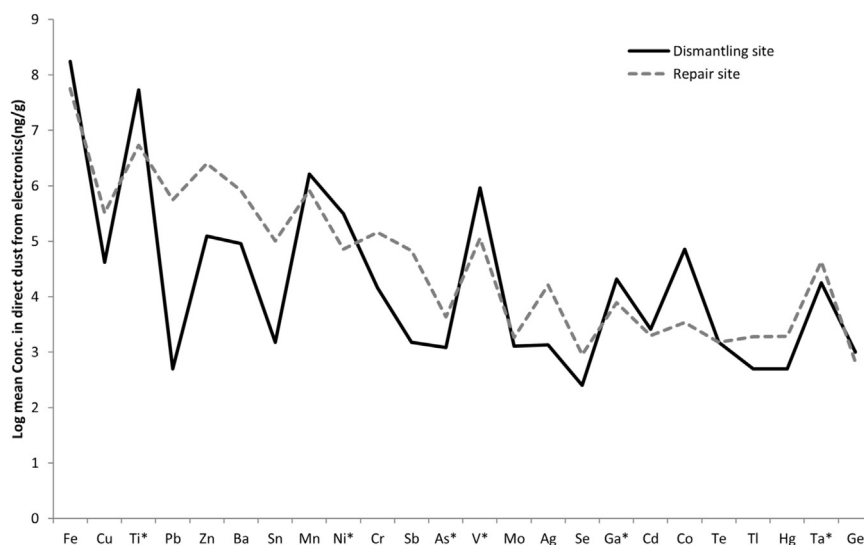
Fig. 7. Metal concentrations in direct dust from electronics. Metal concentrations with significant difference are indicated with*.

unsafe/informal manner (Ogungbuyi et al., 2012; Balde 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 (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) into the soil, and from the soil at burning and dismantling sites into the shops (contaminating floor dust).

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 38,530 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 21,270 mg/kg (Cu) were found. We found Pb levels in floor dust 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
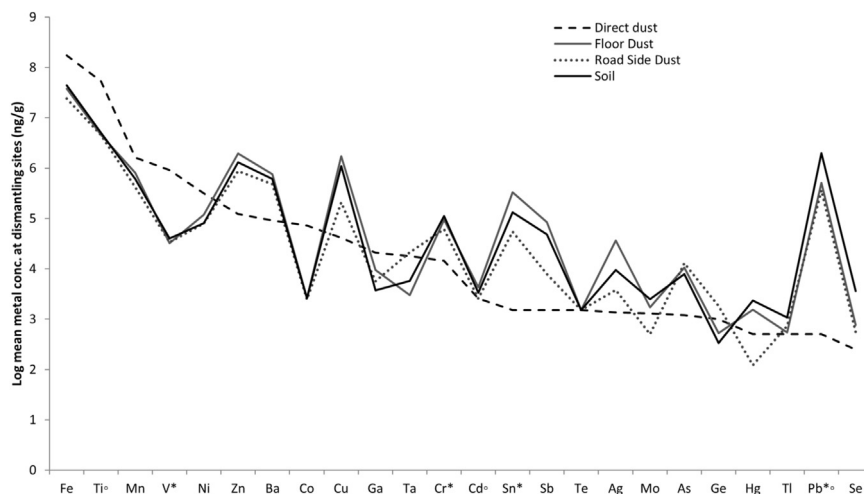

Fig. 8. Metal concentrations in various samples. Metal concentrations with significant difference are between the locations (indicated with°) and activities (indicated with*).

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 bioavailability 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 systems 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 < dismantling sites < burning sites. In addition, the PLI showed soils as being most polluted floor dust and roadside dust (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 < dismantling 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 actiivities 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 for 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.

Metal concentrations in roadside soils/dust reflect the pollution levels from anthropogenic sources in urban areas. Overall, the pollution load indices (PLI) of floor dust and roadside soils/dust 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 dust in 2007 and 2008 as reported by Nduka and Orisakwe (2010). In addition, the metal concentrations (Pb, Cd, Cr) in roadside dust 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 dust from repair sites in the same location (Ibadan). This is an indication of contamination in the indoor environment.

4.2. Implications of high metals concentrations in the environment

No doubt, e-waste recycling is a 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 groundwater, 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 anaemia, 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 et al., 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 than the concentration reported in studies in China (Yekeen et al., 2016; Awasthi et al., 2016a). 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 deterioratation as a result of informal e-waste recycling. Nigeria is a representative of e-waste recycling in developing countries, and a solution proffered for Nigeria can be applied in other countries.

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 exceed the concentrations at control sites by 100 s to 1000 s times on most of the metals. Our findings provide a evidence for an urgent need to develop effective strategies to strengthen enforcement of existing international and national e-waste regulations to curb the environmental and health risks posed by informal e-waste recycling presently and the unforeseen future. Comparing our results with past studies in the same locations, the metal concentrations are increasing, suggesting that the situation calls for urgent action.

Contributorship statement

This study is part of the Ph.D. research of CMO. CMO conceived the study, carried out the literature review, developed data collection and analyses plan, collected data, analysed the data, drafted the manuscript and provided critical revisions to the manuscript. WP and MV are the supervisors and were involved in study design, data collection plan, revision of the various versions of the manuscript, and made contributions to the manuscript. PMB was involved in all stages of the write-up and critical revision of the manuscript and contributed to the data analyses and advanced statistical procedures.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2018.03.002.

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