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Environmental impact and health risk assessment of potentially toxic metals emanating from different anthropogenic activities related to E-wastes

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ABSTRACT

The global desire for modernization through technology has thrown up a major disposal challenge for e-wastes, especially in low-economic countries. This study assessed the environmental impacts and possible health risks of potentially toxic metals emanating from poorly managed e-wastes across three main representative sites in southwest Nigeria. Soil samples were collected from three major cities in Southwestern Nigeria and analyzed for As, Cd, Pb, Cu, Cr, Ni and Zn. Pollution assessments were done using indices including contamination factor (C_f), pollution load index (PLI) and potential ecological risk index (PERI) coupled with evaluation of non-cancer and cancer health risks. Results showed enrichment of the local soil with metals due to e-wastes related activities, with an elevated level of C_f (>6), revealing that the soils around the e-waste dumpsites were severely contaminated. In addition, the assessment of individual metal potential ecological risk index (E^i_f) showed a high level of potential ecological risk for Cd (E^i_f >320) at all the sites while As, Pb, Cu and Ni exhibited high ecological risk at the sites, especially at topsoil layer. Furthermore, the study established varying potentials for carcinogenic health risks for residents around the dumpsites, such that while a negligible risk index occurred for Cd and Ni ($RI < 10^{-6}$), the risk is tolerable for Pb ($10^{-6} < RI < 10^{-4}$) but within cancer-development range for As and Cr ($RI > 10^{-4}$). The study concluded that poorly managed e-wastes in the area poses significant threats to the health of humans and the entire ecosystem. Further study is recommended to identify similar e-waste dumpsites at regional and national – scales for sustainable restoration and improved e-waste management.

1. Introduction

The production and sale of electrical and electronic equipment has skyrocketed globally over the past decades due to the major evolution in the high-tech sector of the electronic industry (Deng et al., 2016). This has led to a mass production of diverse electronic gadgets but not without the consequence of the huge accumulation of redundant electronics as e-waste. Although e-waste is not desirable, the fast-growing volume of e-waste is principally powered by greater consumption rates of electrical and electronic equipment due to consumers' lifestyles, the short life cycles of the gadgets, and limited repair options for malfunctioned gadgets (Forti et al., 2020). The consequence of a high rate of obsolescence with most of the outdated gadgets ending up in the environment with poor understanding of the hazards that such materials pose to humans and the environment has called for concerns in many parts of the world (Sitaramaiah and Kusuma, 2014; Awasthi et al., 2016; Dasgupta et al., 2017; Ikhlayel, 2018; Ravindra and Mor, 2019; Singh et al., 2020; Wang et al., 2020).

The amount of e-waste generated, globally, was estimated to be 41.4 Mt in 2014, by 2016 it has increased to 44.7 Mt or 6.1 kg per inhabitant, amounting to 8% increase (3.3 Mt) in two years (Balde et al., 2015; Iqbal et al., 2015; Heacock et al., 2016; Baldé et al., 2017); it exceeded 46 Mt in 2017. According to Forti et al. (2020), a remarkable 53.6 Mt of e-waste was generated globally in 2019 to give an average of 7.3 kg per capita, and this is anticipated to grow to 74.7 Mt by 2030 making the difference to be almost doubling since 2014. Forti et al. (2020) also noted that of the 53.6 Mt of e-waste that waste generated in 2019, only 9.3 Mt (17.4%) was recycled, indicating that the recycling practices do not meet up with the pace of the global growth of the waste. Consequently, the fate of the remaining 82.6% which amount to 44.3 Mt remains unclear; they are likely indiscriminately disposed, refurbished and traded as second-hand

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products or recycled under inadequate conditions, especially in developing nations (Singh et al., 2020; Wang et al., 2020; Forti et al., 2020).

In general, there is a huge difference in the quantity of e-waste generated in the developing countries compared to the developed countries. In 2019, a total of 50 Mt of e-waste was generated in Asia, America and Europe while Africa generated only 2.9 Mt and Oceania had a record of 0.7 Mt. In terms of e-waste generation per capita, Europe led the pack with 16.2 kg per capita, closely followed by Oceania with 16.1 kg per capita. America, Asia and Africa generated 13.3, 5.6 and 2.5 kg per capita respectively (Forti et al., 2020). However, most of the e-wastes generated in the developed countries are exported to developing nations, especially India, Nigeria, Ghana and Pakistan. Though many of these nations have adopted international and regional instruments that make it illegal to import hazardous wastes into other nation, including the Basel Convention (1989) and the Bamako Convention (1991) (Kummer, 1992; Khan, 2016), lax in governmental regulations, regulatory ambiguities as well as corruption have been found to compromise the rules and thereby making room for illegal importation of e-wastes in form of used electronics across international borders. Consequently, many redundant electronic equipment have found their ways into many of the developing countries, including Nigeria (UNEP, 2011; Staffan, 2011; Terada., 2012; Sthiannopkao and Wong, 2013; Iqbal et al., 2015; Heacock et al., 2016; Baldé et al., 2017; Wang et al., 2020; Forti et al., 2020).

A major factor that drives the trade of obsolete electronic gadgets by low and middle income populations is economic benefit (Arshadi et al., 2018; Davis et al., 2019; Islam et al., 2021). Arshadi et al. (2018), among others, found that e-wastes may contain up to 60% rare and precious metals due to their excellent conductivity, suggesting that valuable materials can be recovered from some e-wastes. Nonetheless, e-waste has been generally confirmed to contain a high level of potentially toxic metals; including lead, cadmium and copper, which have been linked with hazardous effects on humans and the environment, in circuit boards, batteries and electrical wiring (Stevels et al., 2013; Tang et al., 2010; Zeng et al., 2013; Awasthi et al., 2016). The consequence of non-existent or inadequate infrastructure to manage the disposal and recycling of the large percentage of the e-wastes effectively is habitual contamination of the environments and a significant exposure of people, including children, to harmful chemicals (Lundgren, 2012; Olafisoye et al., 2013; Heacock et al., 2016; Singh et al., 2020). The contaminants, which might occur directly through the recycling process or indirectly by ecological exposure, pose considerable risks to human health (Purchase et al., 2020; Alabi et al., 2021; Kumar and Gupta, 2021).

Among the various components of e-wastes, the potentially toxic metals are of immense concern because of their various adverse effects and the indestructible nature of metals which makes them prevalent in the environment leading to an increase in human exposure (Kumar and Gupta, 2021). Many reports of indiscriminate dumping of e-wastes in their immediate environment or with other domestic solid wastes are indicators of poor understanding of the dangers of e-waste in many sub-Saharan countries, including Nigeria (Bimir, 2020; Maphosa and Maphosa, 2020; Nnorom and Odeyingbo, 2020; Alabi et al., 2021) Besides, the primitive recycling processes involve mostly young people, including minors, as scavengers searching through solid waste heaps at dumpsites of e-wastes without any concern about the health implications of such dangerous means of livelihood (Obaje, 2013; Popoola et al., 2019). A larger number of the populace that reside around such primitive recycling factories are at higher risk due to their continual exposure to harmful materials emanating from the recycling activities and processes that are mostly done without any safety measures.

This study therefore focused on the assessment of the environmental impacts and possible health risks of potentially toxic metals emanating from e-waste related anthropogenic activities in three locations, where e-wastes enter the environment through different activities: (i) a dumpsite in a used-electronics market, where samples were collected to assess the impact of the ongoing activities of the factory on the location and the possible effects on the immediate environment (ii) an open-space primitive e-waste recycling working area and its environment, where samples were collected from this site with the intention to evaluate the impact of dumping e-waste in the environment according to either ongoing or previous use of the land with respect to e-waste dumping; and (iii) surroundings of public buildings (offices and institutional residences) with e-wastes scattered around - as an example of a typical domestic indiscriminate dumping of e-wastes.

2. Materials and methods

2.1. Study area

Soil Samples were collected from three major cities in the South-Western part of Nigeria that cut across two States; Osun and Oyo States (Figure 1a). The first site, which is located in Osogbo, the administrative capital of Osun State is an open-air primitive e-waste recycling site, where manual dismantling and burning of electronics, to extract valuable materials, take place on a daily basis without any environmental protection or safety measures. This location has been in operation for over two decades and it is located within residential area; close to many food vendors and other small business operators. It has a seasonal stream that has its course running through the center of the operation of the factory. It is on the geographical grid latitude 7.7710 ºN and longitude 4.5570 ºE (Figure 1(bi)). The second site is in Ibadan, the administrative capital of Oyo State (7.4019° N, 3.9394° E; Figure 1(bii)). The location is an illegal e-waste dumpsite where nonfunctional electronics are dumped and burnt on regular basis and has been in existence for over three decades. It is located within the vicinity of a major market and beside a warehouse along the Iwo road axis of the megacity. The market and the warehouse are known for the sales of used-electronics; such as TV sets, printers, radios, computers, DVD players etc. Samples were collected from this site with the intention to evaluate the impact of dumping e-waste in the environment according to either ongoing or previous use of the land with respect to e-waste dumping. The third site is within a University campus in Ile-Ife, Osun state; with geographic grid reference 7.4895° N, 4.5509° E (Figure 1(biii)). Samples were collected from areas where over the years, obsolete and damaged laboratory equipment, computers and printers, as well as fluorescent tubes and bulbs are dumped indiscriminately and are occasionally burnt. Samples were collected to assess the potential impact of the indiscriminate deposition of e-waste in our immediate environment, representing typical none intentional pollution of the environment through careless dumping of wastes, especially around office buildings and residences. The typical representation of the physical appearance of the e-waste dumps at each of the locations is shown in Plate 1 (a–c) respectively for Ibadan, Osogbo and Ile-Ife locations.

2.2. Sampling

Seventeen composite soil samples were collected from three sampling sites. Each site was divided into six sampling areas, except for the Ile-Ife site which was divided into five sampling area to make a total of 17 mapped out areas/block, representing different activities related to e-waste or at certain distance from a dumpsite centre (Details in Table S1, supplementary information). To obtain a true representation of each targeted sampling area/block, the soil samples were collected using a systematic sampling unit block strategy (ITRC 2012; Isimekhai et al., 2017) for all the areas sampled. Samples were collected from at least 5 spots for each of the sampled areas, depending on the size of the area, to make a composite sample for that particular block, Soil samples were thereafter obtained from each stratum in triplicates and across two main soil profiles (0–15 cm and 15–30 cm), representing the top and sub soil profiles, respectively, with the aid of a soil auger. A hand-held global positioning system (GPS, Garmin model) instrument was used to capture the coordinates of each sampling sites. Cross contamination was prevented by ensuring that the auger was cleaned properly in-between samples. Soil samples were collected in polyethylene bags with proper

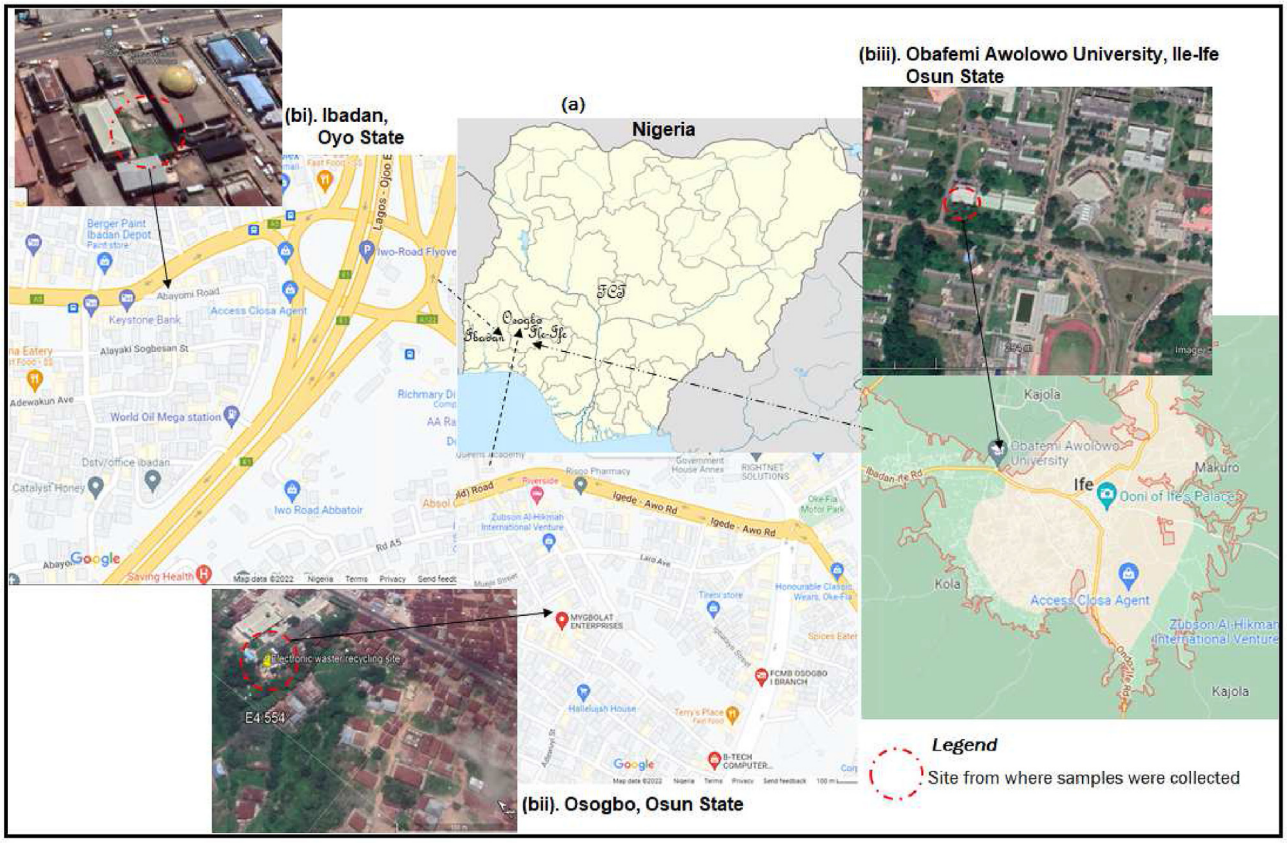

Figure 1. (a) Map of Nigeria with the study areas identified on it, (b) Google maps showing the aerial views of the study areas (i – iii, open space primitive recycling factory in Osogbo, E-waste dumpsite in Ibadan, and office surroundings with indiscriminate deposit of e-waste around building in Ile-Ife).

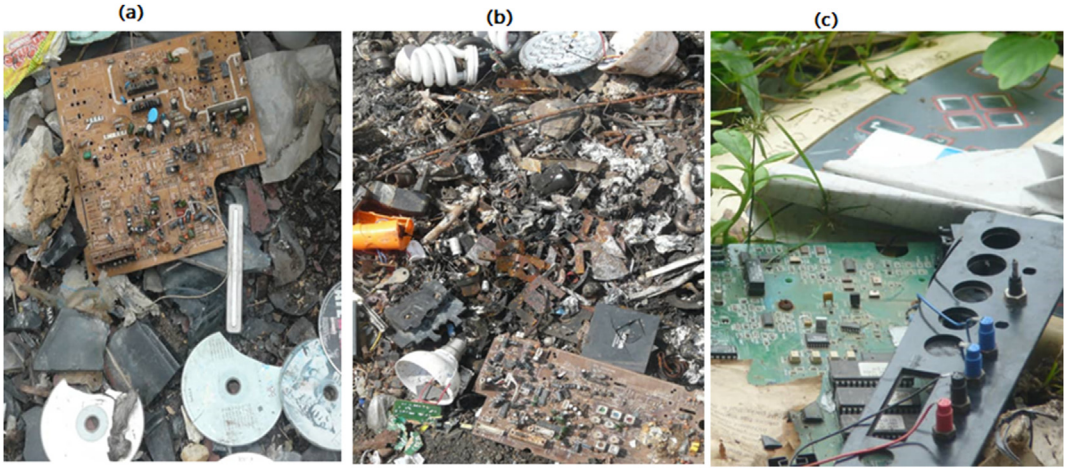

Plate 1. a–c: Typical representation of the physical appearance of the e-wastes dumped at Ibadan, Osogbo and Ile-Ife locations, respectively.

labeling. The samples were air dried and sieved to remove any pieces of plastic or any broken electronics parts and other bigger debris. Samples were then stored at room temperature until further work. The control sample for each site was taken at a minimum of 500 m away from each site.

2.3. Sample digestion

The soil samples were dried in the laboratory at the prevailing room temperature (24.6°C ± 3.5 °C) for two weeks then thoroughly mixed together to have a homogeneous composite sample of each sampling area. A portion of each composite sample was then ground into a fine particles size using agate mortar and sieved through a mesh with pore size of 63μm. Accurately weighed 0.25 g of the pulverized soil sample was transferred into a Teflon beaker and digested with 10 mL of aqua regal reagent (HNO_3: HCl; 3:1) on a thermostated hot plate (at a temperature between 170–200 °C) in a fume hood. After about an hour, 5 mL of hydrofluoric acid (HF) was added. The content of the Teflon beaker was replenished with the addition of more HNO_3 and HF (3:1 v/v) to avoid total evaporation, until the soil sample was ascertained digested. The mixture was allowed to evaporate completely and the residual redissolved in 1 mL of HNO_3, and then 10 mL of deionized water was

added and mixed. The solution was filtered with No 40 Whatman filter paper, transferred into a 50 mL volumetric flask and made up to mark with deionized water. Blank samples were also prepared to ascertain the background levels of the metals in the reagents used for the sample digestion, using the method described but without the sample. Digested samples were stored at 4 °C prior to analysis. Metal analysis (Cd, As, Pb, Cu, Cr, Ni, and Zn) was done using Flame Atomic Absorption Spectrophotometer (FAAS) (Spectra AA 55B, Varian Australia Pty-Ltd, Mulgrave Victoria, Australia). Self-reversal background correction was employed, and a hydride unit was used for arsenic determination.

2.4. Quality assurance/control

All reagents used were of analytical or higher grade and were used as received. Hydrochloric acid was from BDH Laboratory supplies, Poole Bon, England, Nitric acid (63%) was purchased from Kermel, Tianjin, China and Hydroflouric acid (40%) was from LobaChemie laboratories, Mumbai, India. The standard mixture for the calibration of the Atomic Absorption Spectrometer was ICP multi-element standard solution IV (111355) obtained from Merck. All the laboratory wares used in this study are non-glass (polyethylene): volumetric flasks for making up the digested sample to 50 mL, sample bottles for storing the digested samples, cylinders and beakers. Teflon beakers were used for the digestion process. All these were thoroughly washed with liquid detergent and soaked in 10% nitric acid (HNO_3; v/v) for 48 h. After which they were thoroughly rinsed with deionized water. The non-volumetric wares were then oven dried for 12 h at a temperature of 80 °C before use.

As part of quality assurance, precision was determined in terms of reproducibility of data by preparing and analyzing the samples in a replicate of three. The accuracy and efficacy of the digestion procedure were assessed using the percentage recovery values from the analysis of a certified reference soil material (IAEA Soil-7). To assess the effect of the sample matrix on the efficiency of the analytical procedures used, soil samples spiked with multi-element standard mixture (IV (111355)) at two concentration levels of 5 mg/kg and 50 mg/kg were digested and analysed using the described procedures.

2.5. Evaluation of the pollution level of the soil and the potential ecological risk

In the effort to assess the impact of the e-waste on the soil of the study area and the possible ecological risk resulting from the land use/activities observed in the study area, different pollution indices: including Geo-accumulation index (I_{geo}), Contamination factor (Cf), pollution load index (PLI), and potential ecological risk index (PERI) were used.

2.5.1. Geo-accumulation index (Igeo)

The geo-accumulation index as proposed by Muller (1969) was used to estimate the enrichment of the environment with metals above the baseline concentrations through anthropogenic activities.

I_{geo} was calculated using Eq. (1).

$$I_{geo} = log_2\left(\frac{C_n}{1.5B_n}\right) \quad (1)$$

Where C_n is the measured concentration of the heavy metal of interest and B_n is the geochemical background concentration or reference value of heavy metal in the local soil. In this study, samples collected from 500 m away from each sampling site was analysed to obtain the reference value of heavy metals in the local soil. Coefficient 1.5 is a factor used to minimize the impact of potential lithogenic variations in soil (Al-Haidarey et al., 2010).

The method measures the degree of metal pollution in terms of seven enrichment levels built on the increasing numerical values of I_{geo}: unpolluted (I_{geo} <0), unpolluted to moderately polluted (0 < I_{geo}<1), moderately polluted (1 < I_{geo}<2), moderately to strongly polluted (2 < I_{geo}<3), strongly polluted (3 < I_{geo}<4), strongly to extremely polluted (4 < I_{geo}<5), extremely polluted (I_{geo}>5).

2.5.2. Contamination factor and pollution load index

The contamination factor describes the impact of an individual metal on the environment. It was obtained as the ratio of the concentration of the target metal in the contaminated/study environment to that of the background/reference level (Hakanson, 1980), Eq. (2).

$$C_f^i = \frac{C_{sample}^i}{C_{background}^i} \quad (2)$$

where: C^i_{sample} refers to the concentration of the metal of interest in the sample (mg/kg) and $C^i_{background}$ indicates the concentration of the metal of interest in an unpolluted environment/environmental background level (mg/kg). Based on the Hakanson (1980) theory: when C^i_f <1, the soil has low contamination, 1 < C^i_f <3 indicates moderate contamination, 3 < C^i_f <6 shows considerable contamination while a C^i_f >6 is an indication of very high contamination. The pollution load index (PLI) was then used to evaluate the contamination caused by all the potentially toxic metals determined in the study area, following the equation proposed by Tomlinson et al. (1980). PLI was calculated for a single site as the nth root of n number of metals multiplying the contamination factors (C_f values) combined, Eq. (3).

$$PLI = (C_f^1 \times C_f^2 \times C_f^3 \times \ldots \times C_f^n)^{\frac{1}{n}} \quad (3)$$

where n = the number of metals determined.

According to Tomlinson et al. (1980) and buttressed by Liu et al. (2005), a PLI <1 indicates that the metal loads have no significant impact on the studied environment and are close to the background, while a PLI >1 shows that the environment has been polluted by the metal load. However, based on the comprehensive interpretation for contamination degree proposed by Angulo (1996), PLI <50 is an indication of no intervention required while 50 ≤ PLI <100, means that more detailed study will be required to monitor the site, and PLI ≥100 indicates that the site will require immediate intervention to stop or remediate the pollution.

2.5.3. Potential ecological risk index (PERI)

The PERI was used to evaluate quantitatively the environmental risk due to the existence of potentially toxic metals in the soil of the study area. The model was proposed by Hakanson (1980) and has been widely employed to assess the potential ecological risk caused by overall heavy metals (Islam et al., 2015; Isimekhai et al., 2017). The model reflects the comprehensive impacts of different potentially toxic metal in the environment by considering systematically the metal concentration, its biotoxicity, migration regularity, and influence on the regional background value. It therefore, signifies the sensitivity of the biological community to the metal toxicity and demonstrates the potential ecological risk caused by the overall metal contamination. This is calculated using Eq. (4).

$$PERI = \sum_{i=1}^{n} E_f^i \quad (4)$$

where, E^i_f is the potential ecological risk index for a single metal pollution and can be calculated with Eq. (5)

$$E_f^i = C_f^i \times T_f^i \quad (5)$$

Where, T^i_f is the biological toxic response factor for a specific metal or an individual metal toxicity response coefficient. According to Hakanson's model, the toxic-response factor, T^i_f, values are: As = 10, Cd = 30, Pb, Ni & Cu = 5, Cr = 2, and Zn = 1 (Hakanson, 1980; Islam et al., 2015; Isimekhai et al., 2017). The values for E^i_f have been interpreted to indicate the intensity of the risk posed by an individual pollutant to the

environment. These are graded as: low ecological risk (E^i_f <40); moderate ecological risk (40 ≤ E^i_f <80); considerable ecological risk (80 ≤ E^i_f <160); high ecological risk (160 ≤ E^i_f <320); and extreme high ecological risk (E^i_f ≥320). In the same vein, the intensity of the risk emanating from the pollution caused by the combined metals follow the order, PERI <150 (low ecological risk); 150 ≤ PERI <300 (moderate ecological risk); 300 ≤ PERI <600 (considerable ecological risk); and PERI ≥600 (very high ecological risk) (Hakanson 1980; Shi et al., 2006; Yu et al., 2017; Islam et al., 2015; Isimekhai et al., 2017).

2.6. Human health risk assessment

Health risk assessment of the topsoil in an environment is a good means to evaluate both carcinogenic and non-carcinogenic risks to human based on the three pathways (ingestion, dermal contact and inhalation) through which man is exposed to harmful substances in the environment. Using the guidelines and Exposure Factors set by the US Environmental Protection Agency (USEPA, 1989, 1997, 2001; Qing et al., 2015; Li et al., 2019), we were able to measure the health risk of the potentially toxic metals analyzed from the samples. The average daily doses/exposures (ADDs), measured in mg/Kg day, of potentially toxic metals through the three pathways: ingestion (ADD_{ing}), dermal exposure (ADD_{derm}) and inhalation (ADD_{inh}) for both children and adults calculated using Eqs. (6), (7), and (8):

$$ADD_{ing} = \frac{C_{soil} \times IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (6)$$

$$ADD_{dermal} = \frac{C_{soil} \times SA \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (7)$$

$$ADD_{inh} = \frac{C_{soil} \times InhR \times EF \times ED}{PEF \times BW \times AT} \quad (8)$$

Where: *IngR is the ingestion rate of soil (mg/day) (200 for children, 100 for adults), InhR is the inhalation rate of soil (m^3/day) (7.6 for children, 20 for adults), EF is the exposure frequency (day/year) (350 for both children and adults), ED is the exposure duration (year) (6 for children, 26 for adults), BW is the body weight (Kg) (15 for children, 70 for adults), AT is the average time for carcinogenic (non-carcinogenic) effect (day) (365 x ED), ABS is the dermal absorption factor (0.001), SA is the exposed skin area (cm^2) (860 for children, 1530 for adults), AF is the adherence factor (mg/cm^2) (0.2 for children, 0.07 for adults), and PEF is the particle emission factor (m^3/Kg) (1.36 x 10^9)* (USEPA, 2011, 2013; Li et al., 2014, 2019).

The non-carcinogenic risk was evaluated using the hazard quotient (HQ) and hazard index (HI), which are calculated using Eqs. (9) and (10).

$$HQ_i = \frac{ADI_i}{RfD_i} \quad (9)$$

$$HI = \sum_i^n HQ_i = \sum_i^n \frac{ADI_i}{RfD_i} \quad (10)$$

ADI_i is the average daily intake of a specific metal (mg/Kg), RfD_i is the reference dose (mg/Kg day) for the same exposure pathway(s) (USEPA, 1989; Qing et al., 2015; Li et al., 2019). RfD_i is the maximum daily dose of a metal from a specific exposure pathway that will not cause a significant risk of harmful effects to an individual during a lifetime. When HQ < 1, it indicates that there will be no adverse health effects, while HQ > 1, indicates the possibility of adverse health effects (USEPA, 1989, 2001; Qing et al., 2015). HI is the sum of HQ and indicates the total risk of non-carcinogenic elements via three exposure pathways associated with an element. So, HI < 1 is an indication of no risk and HI > 1is an indication of a non-carcinogenic risk to the human body, and as the value of HI increases the non-carcinogenic risk increases (Qing et al., 2015).

The carcinogenic risk (RI), the likelihood for an individual to develop any type of cancer in lifetime due to exposure to carcinogenic risks (Li et al., 2014), was estimated using the method used by other researchers (Wei et al., 2015; Chabukdhara and Nema, 2013; Diami et al., 2016; Qing et al., 2015; Li et al., 2019) and calculated using Eq. (11).

$$RI = \sum_i^n ADI_i \times SF_i \quad (11)$$

Where: SF represents the probability of developing cancer per unit exposure level (mg/kg day) with values that depend on the exposure route. The standard values for RfD and SF are shown in Table S2, supplementary information. The model show that RI < 10^{-6} means the carcinogenic health risk from the environment can be ignored; when 10^{-6} < RI < 10^{-4}, the carcinogenic health risk is tolerable to human health and social stability; when RI > 10^{-4}, is an indication that the carcinogenic health risk has a high tendency of causing cancer development in man (Wu et al., 2015; Qing et al., 2015; Li et al., 2019).

3. Results and discussion

3.1. Quality control

The results of the quality control measures taken to ensure the accuracy of the results obtained and effectiveness of the analytical procedures are presented in Table 1. The percentage recovery values of the metals analysed from the certified reference soil material (IAEA Soil-7) gave results ranging from 94.33 % for arsenic to 104.12 % for nickel while the percentage recovery for the spiked samples varied from 91.80 % for arsenic to 99.40% in chromium at the 5 mg/kg spiked level and from 92.16 % for arsenic to 101.72 % for chromium at the 50 mg/kg spiked. The percentage relative standard deviation (% RSD) for a triplicate analysis of the samples, as a measure of reproducibility of the results was <15 % in all cases. The high percentage recovery levels obtained for the certified reference soil material and the spiked samples showed that the analytical methods used in this study are efficient with little influence of the sample matrix. The level of the metals determined in the blank samples were below the detection limits, thereby eliminating the possibility of potential contamination from the chemicals and reagents used.

3.2. Potentially toxic metals concentration and distribution in the study area

A wide range of concentrations was observed for the analyzed metals across all the study locations. The descriptive statistics of the metals concentrations (Table 2) showed the average abundance of the metals following the order of As < Ni < Cd < Cr < Pb < Cu < Zn, for the top-soil, and Ni < As < Cd < Cr < Pb < Cu < Zn, for sub-soil, at the Ile-Ife location while at Osogbo and Ibadan locations, similar trends were obtained for both top-soil and sub-soil, and followed the order of Cd < Ni < As < Cr < Zn < Pb < Cu. The concentrations of the metals in the topsoil varied spatially as described by the boxplots in Figure 2 At the primitive e-waste recycling site (Osogbo location), the levels of the metals varied between 24.5 and 153.6, 33.3 and 72.7, 262.4 and 935.3, 409 and 1120, 74 and 159.9, 47.9 and 94.3, 246.6 and 571 μg/g, respectively for As, Cd, Pb, Cu, Cr, Ni, and Zn. At the e-waste dumpsite (Ibadan location), the concentration of metals ranged from 86.6 - 226.1, 57.8–111.3, 361.3–894.2, 391.8–930.6, 117.3–236.5, 105.4–142, 286–718.3 μg/g, respectively for As, Cd, Pb, Cu, Cr, Ni, and Zn, while at the office environment in Ile-Ife where e-wastes were indiscriminately disposed in the environment, concentrations ranged from 48.4 - 86.3, 57.6–116.4, 119.8–245.3, 129.5–250, 92.7–198.3, 40.1–86.3, 273.1–351.3 μg/g, respectively for As, Cd, Pb, Cu, Cr, Ni, and Zn. For As and Zn, the mean concentrations are significantly different from one another for the three locations, while only the mean concentration for Cr and Ni are not significantly different for Osogbo and Ile-Ife locations which were significantly different from the mean value obtained for the Ibadan location. The mean concentrations of Cu and Pb are not significantly different for Osogbo and Ibadan

Table 1. Recovery results from the spiked samples and IEAE Soil-7 Certified Reference Material.

Spiked samples (n = 3)							IAEA Soil-7 (n = 3)			
Metal	Spiked Conc. (mg/kg)	Recovered Conc. (mg/kg)	% Recovery	Spiked conc. (mg/kg)	Recovered conc. (mg/kg)	% Recovery	Certified conc. (mg/kg)	Obtained Conc. (mg/kg)	95% Confidence Interval	% Recovery
Cd	5.00	4.64 ± 0.36	92.80	50.00	46.91 ± 0.87	93.82	1.30	1.24 ± 0.32	1.1–2.7	95.61
Pb	5.00	4.68 ± 0.45	93.60	50.00	47.38 ± 2.92	94.76	60.00	59.72 ± 1.61	55–71	99.53
As	5.00	4.59 ± 0.51	91.80	50.00	46.08 ± 1.75	92.16	13.40	12.64 ± 1.91	12.5–14.2	94.33
Cu	5.00	4.75 ± 0.45	95.00	50.00	48.41 ± 1.02	96.82	11.00	10.82 ± 1.09	9–13	98.36
Ni	5.00	4.83 ± 0.39	96.60	50.00	48.96 ± 1.95	97.92	26.00	27.07 ± 1.82	21–37	101.11
Zn	5.00	4.89 ± 0.45	97.80	50.00	49.24 ± 2.88	98.48	104.00	103.95 ± 5.11	101–113	99.95
Cr	5.00	4.97 ± 0.49	99.40	50.00	50.86 ± 1.99	101.72	60.00	61.87 ± 2.36	49–74	103.12

Table 2. Descriptive statistics of the concentrations of the selected metals in the soil of the study Locations.

Sites	Metals	0–15 cm depth (Topsoil)						15–30 cm depth (Subsoil)						Control sample
		Minimum	Mean	Maximum	Std. error	Median	Coeff. Var	Minimum	Mean	Maximum	Std. error	Median	Coeff. Var	
		Concentration (μg/g)					%	Concentration (μg/g)					%	Mean (μg/g)
Osogbo	As	24.5	110.8	153.6	9.7	117.2	37.1	15.4	85.8	137.0	8.8	91.5	43.3	1.9
	Cd	33.3	60.8	72.7	2.9	64.4	20.5	21.3	49.5	64.0	3.3	55.6	28.4	0.7
	Pb	262.4	707.9	935.3	53.7	755.1	32.2	148.0	579.7	837.0	55.0	638.7	40.2	6.8
	Cu	409.0	885.1	1120.0	54.5	934.8	26.1	195.0	686.9	932.3	57.9	724.0	35.8	6.7
	Cr	74.0	132.5	159.9	6.1	144.3	19.6	47.7	108.7	138.7	7.1	120.2	27.7	5.8
	Ni	47.9	71.4	94.3	3.1	71.5	18.6	35.2	64.8	96.3	4.9	57.8	31.9	3.2
	Zn	246.6	462.7	571.0	24.1	502.5	22.1	131.8	342.0	430.0	23.6	378.2	29.2	16.7
Ibadan	As	86.6	167.5	226.1	10.3	175.5	26.0	76.3	119.4	160.3	6.8	122.8	24.1	2.1
	Cd	57.8	90.2	111.3	3.6	93.5	17.1	48.9	67.3	88.9	3.2	66.4	20.3	0.9
	Pb	361.3	676.5	894.2	43.6	733.5	27.3	228.5	461.1	690.3	43.2	494.5	39.8	8.3
	Cu	391.8	784.1	930.6	43.4	855.7	23.5	258.6	673.3	1009.0	54.4	673.9	34.3	7.2
	Cr	117.3	196.1	236.5	8.7	203.6	18.8	93.9	143.3	190.0	7.5	147.7	22.1	5.9
	Ni	105.4	120.3	142.0	2.7	117.7	9.5	78.3	94.2	111.1	2.0	94.9	9.0	1.7
	Zn	286.0	575.0	718.3	33.0	594.9	24.3	290.3	504.4	582.0	22.9	533.1	19.3	25.3
Ile-Ife	As	48.4	62.5	86.3	2.9	60.5	17.7	27.4	47.4	68.0	3.1	48.4	25.6	2.7
	Cd	57.6	82.4	116.4	5.2	79.6	24.4	40.6	62.9	87.7	3.8	66.1	23.4	0.8
	Pb	119.8	178.8	245.3	11.1	170.6	23.9	83.3	120.3	156.9	5.9	120.6	18.9	7.5
	Cu	129.5	211.1	250.0	10.7	227.7	19.6	108.6	165.3	198.7	8.3	181.0	19.5	9.6
	Cr	92.7	142.7	198.3	9.5	149.9	25.7	71.7	110.0	153.3	7.4	119.7	25.9	5.9
	Ni	40.1	68.9	86.3	3.8	72.6	21.4	28.3	46.2	57.0	2.3	49.5	19.5	8.2
	Zn	273.1	313.3	351.3	7.5	318.2	9.3	220.9	257.1	309.0	7.0	255.9	10.5	12.4

locations which are significantly different from the mean concentrations the for Ile-Ife location, and for Cd, the mean concentrations for Ibadan and Ile-Ife are not significantly different but are significantly different from the mean concentration obtained for the Osogbo location ($p < 0.05$). The high levels of Cu, Pb and Zn compared to others agreed well with the results reported by Isimekhai et al. (2017). The degree of variability of the levels of metals within sampling area was evaluated with their coefficient of variation (CV). Coefficient of variation is typically interpreted to indicate low (CV $\leq$ 20%); moderate variability (CV = 21%–60%); high variability (CV = 61–100%); and very high variability (CV>100%) (Nezhad et al. (2015); Qing et al. (2015), From the results across all the sampling sites, the variability in the concentrations of the metals ranged from low variability to moderate variability with more than 70 % falling in moderate variability. For the Osogbo and Ibadan locations, on the average, the CV of the metals followed the order As > Pb > Cu > Zn > Cd > Cr > Ni, whereas at the Ile-Ife location, the order is Cr > Cd > Pb > Ni > Cu > As > Zn. The mean concentrations of all the studied potentially toxic metals greatly exceeded the background levels of the metals found in the corresponding local soil. This indicates that the soils have been considerably polluted due to the contributions of the anthropogenic activities in the study areas. This revealed the fact that alterations in the morphology, physical or chemical make-up of the local soil can occur due to anthropogenic activities, resulting in severe damage to the soil (Trujillo-González et al.,. 2018; García and Jiménez Ballesta, 2017). In addition, the discrepancies varied with the level of involvement of the locations in e-waste-related activities (Figure 3). Also, it was observed that the metals concentrations in the topsoil are higher in value than in the subsoils but in most cases, they are not significantly different ($p < 0.05$) except for Ni at the Ile-Ife location.

The e-waste deposition and recycling activities may be localized; however, studies have shown that the occurrence of hazardous substances from e-waste can transport further than the processing sites into the ecosystems (Sepúlveda et al., 2010; Zhang et al., 2011). When runoffs of rain from an area contaminated with heavy metals from e-waste dumping site enters into the surrounding water bodies, an elevation in the concentrations of metals in the water bodies occurs even to a level that can make the water unsafe for the use of man and aquatic animals (Olafisoye et al., 2013). The dependence on ground and surface waters by many citizens of Nigeria makes the situation worrisome because water polluted with potentially toxic metals may be consumed ignorantly since

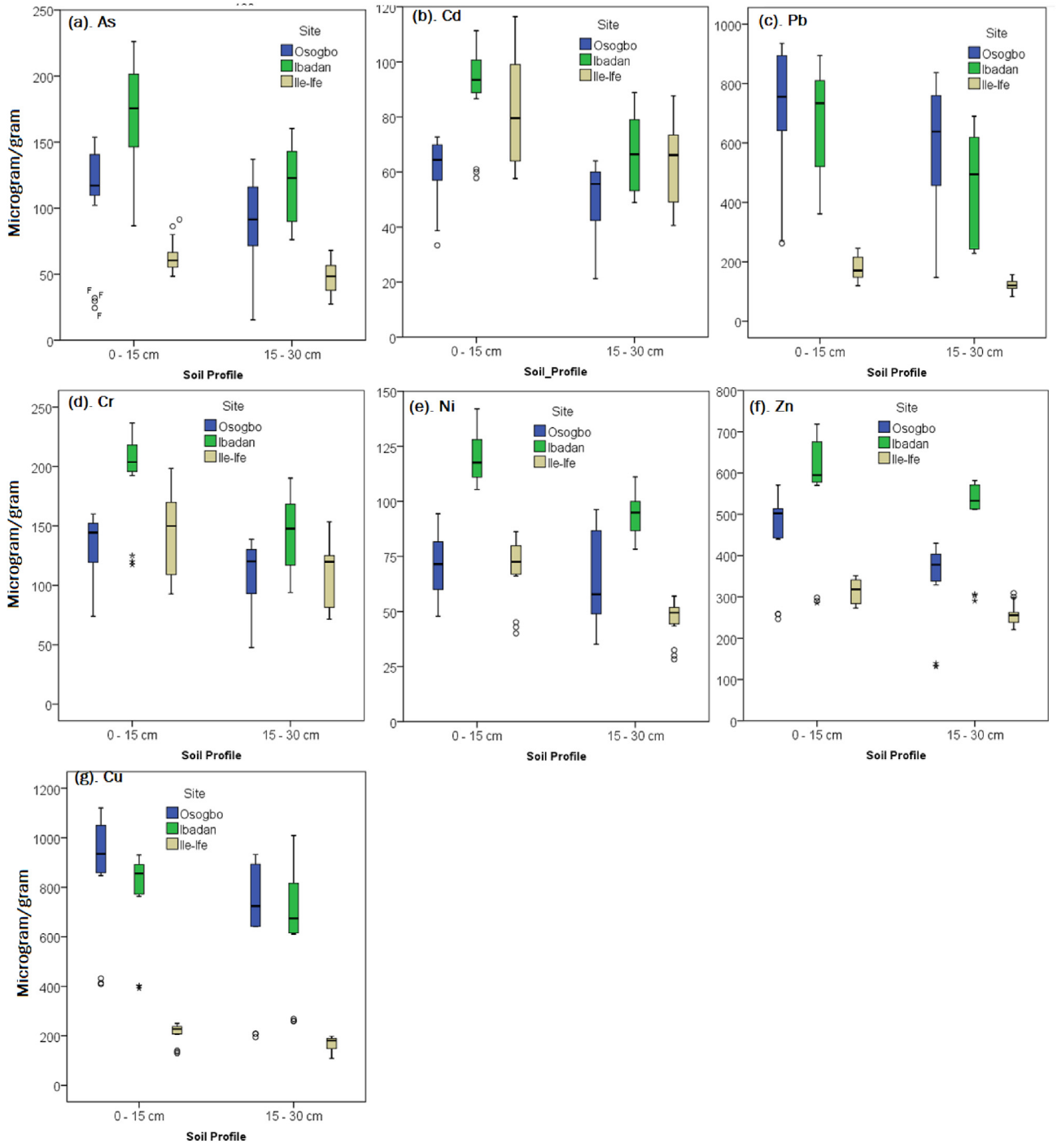

Figure 2. Boxplots of the dispersion (especially minimum, median, maximum and the outliers) in each of the selected metals at the different sampling sites. Note the difference in concentration for each metal.

such water has no change in colour, taste or odour. It is therefore, crucial to pay attention to the existence of e-wastes in any of our environments to ensure human safety and wellbeing.

3.3. Ecological and health risk assessment of potentially toxic metals in the study locations

3.3.1. Potential ecological index and geo-accumulation index

The potential pollution assessment of the study locations was done by means of pollution indices ranking. With the results shown in Figure 4, it is very obvious that the anthropogenic activities tied to e-wastes in the study locations have contributed to the pollution of the soil as shown by the elevated level of C_f, thereby posing danger to the inhabitants of the area and beyond. Applying the interpretation of Hakanson (1980) to the C_f obtained for the study locations: For Osogbo, metals concentrations from the topsoil samples across the site were in the multiple of 15–75, 53–97, 40–136, 62–166, 14–26, 17–28, 15–33, and for the subsoil samples, the concentration was in the multiple of 9–66, 34–85, 23–122, 30–138, 9–23, 14–29, 8–24, for As, Cd, Pb, Cu, Cr, Ni, and Zn respectively, compared to the control site (Figure 4a). For the Ibadan location, the metals concentrations in the topsoil were higher than the control site at a multiple of 41–104, 71–131, 43–107, 54–129, 20–40, 63–80, 11–28, and for the subsoil; 39–75, 62–103, 28–83, 37–140, 16–31, 48–60, 12–23 respectively for As, Cd, Pb, Cu, Cr, Ni, and Zn (Figure 4b). While the

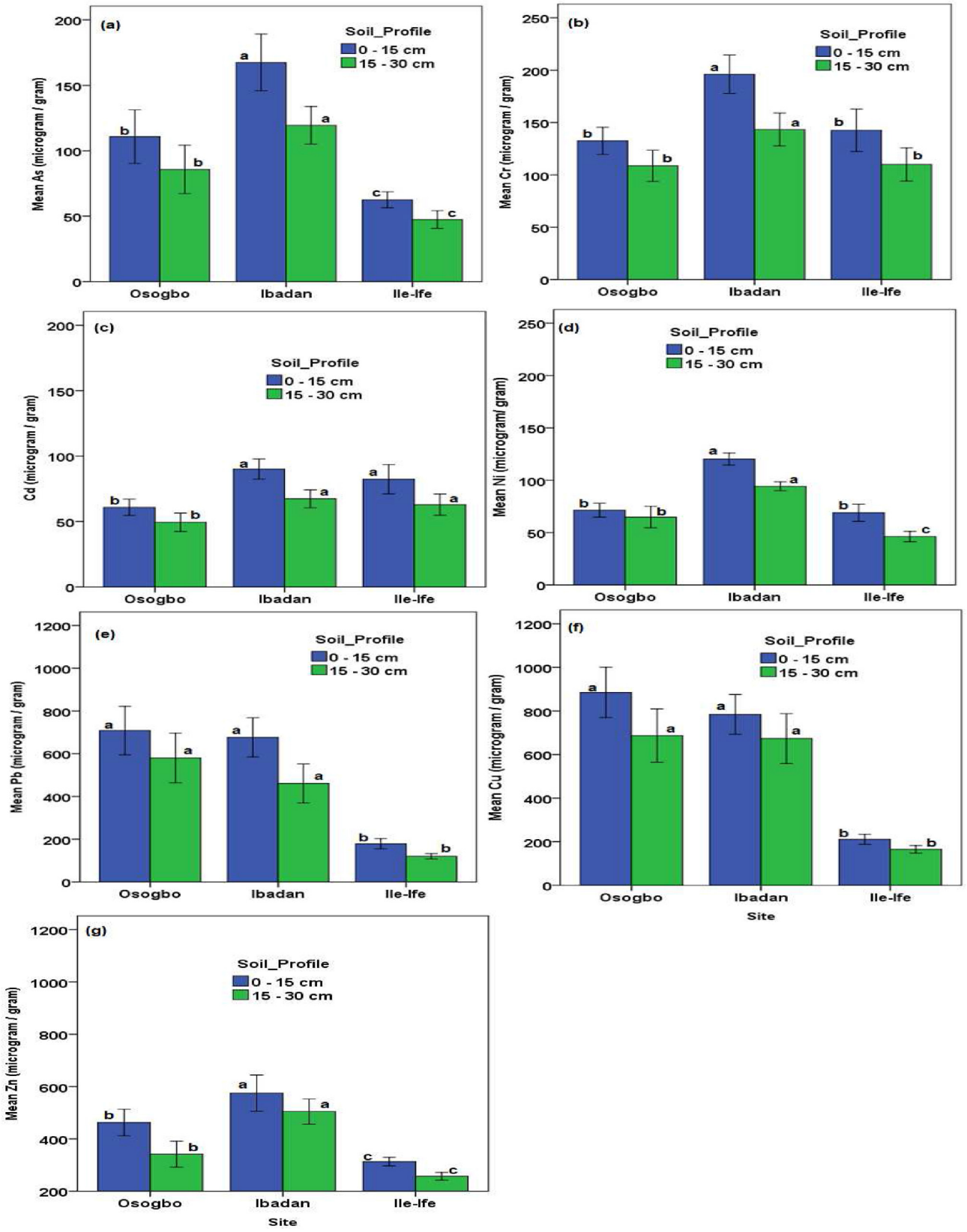

Figure 3. Mean concentrations of the selected potentially toxic metals at the study locations. Corresponding sites of same coloured bar with same alphabets are not significant ($p < 0.05$).

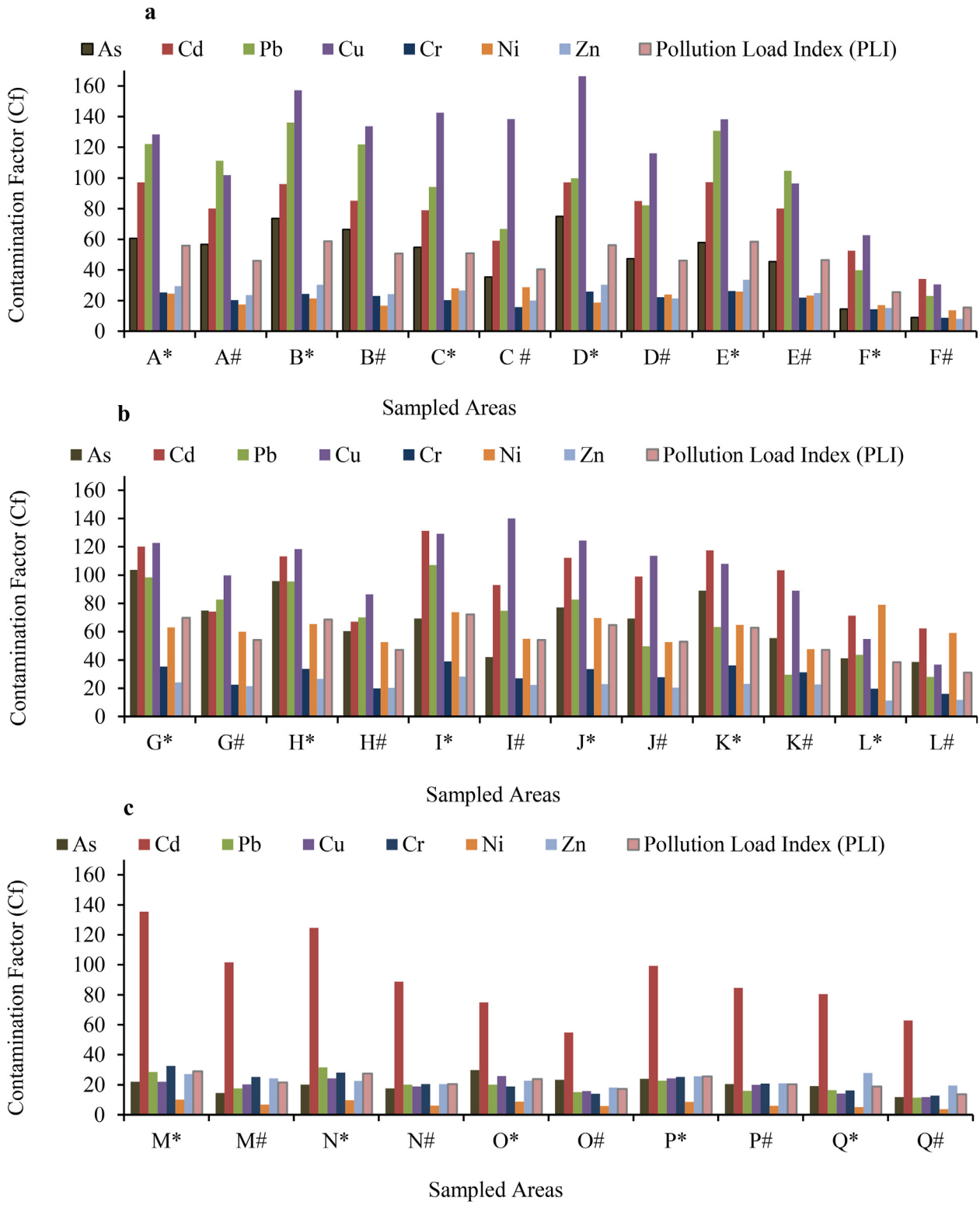

Figure 4. Contamination Factors (Cf) and Pollution Load Index (PLI) assessment of the topsoil of the study locations. a- Cf and PLI for Osogbo site, b- Cf and PLI for Ibadan site, c- Cf and PLI for Ile-Ife site (* = top soil, # = sub soil). *Note: The letters A to Q represent the 17 mapped out area.*

levels of metals in the topsoil of Ile-Ife location has elevated value in the multiple of 19–30, 75–135, 16–32, 14–26, 16–32, 5–10, 22–29, and in the subsoil, the values are higher in the multiple of 12–23, 55–102, 11–20, 12–20, 13–25, 4–7, 18–24 for As, Cd, Pb, Cu, Cr, Ni, and Zn respectively, compared to the control soil samples (Figure 4c). The contamination factor values of the soil samples from the three studied locations, though represented different activities, indicated that the soil of the areas have been severely contaminated by potentially toxic metals. Though the Ile-Ife location was not as contaminated as the other two locations, but it competes well with them for Cd contamination level as opposed to the relatively lower values of C_f obtained for the other metals. Generally, the C_f varied as Cu > Pb > Cd > As > Zn˜Cr˜Ni, Cu > Cd > As˜Pb > Ni > Cr > Zn and, Cd > As˜Pb˜Cu˜Cr˜Zn > Ni for Osogbo, Ibadan and Ile-Ife locations respectively. The PLI the topsoil and subsoils range

from 25 to 59 and 15 to 51 respectively for the Osogbo location, 38 to 72 and 31 to 54 respectively for the Ibadan location, and 19 to 29 and 14 to 21 for the Ile-Ife location (Figure 3). Going by the interpretation of Tomlinson et al. (1980) and Liu et al. (2005), the PLI results showed that all the studied locations have been polluted by the metal load (PLI>1) and moving further, according to Angulo (1996), while the Ile-Ife location requires no intervention yet, the mean PLI value for Osogbo and Ibadan location indicates that monitoring the locations through more detailed study is required (50 ≤ PLI <100).

As shown in Figure 5, the Igeo values obtained from the study varied from location to location and among the various metals determined, though similar for both topsoil and subsoil. At the Osogbo recycling factory area: Igeo values for Cr and Zn were less than 1, indicating no pollution contribution by these metals, with $0 < I_{geo} < 1$ for Ni, it shows that the location is moderately polluted with Ni. However, a significant level of pollution is established for the location by Cu, As, Pb and Cd: with $2 < I_{geo} < 3$, there is an obvious contribution of Cu and As to the pollution level of the location, ranging from moderate to strong pollution effects

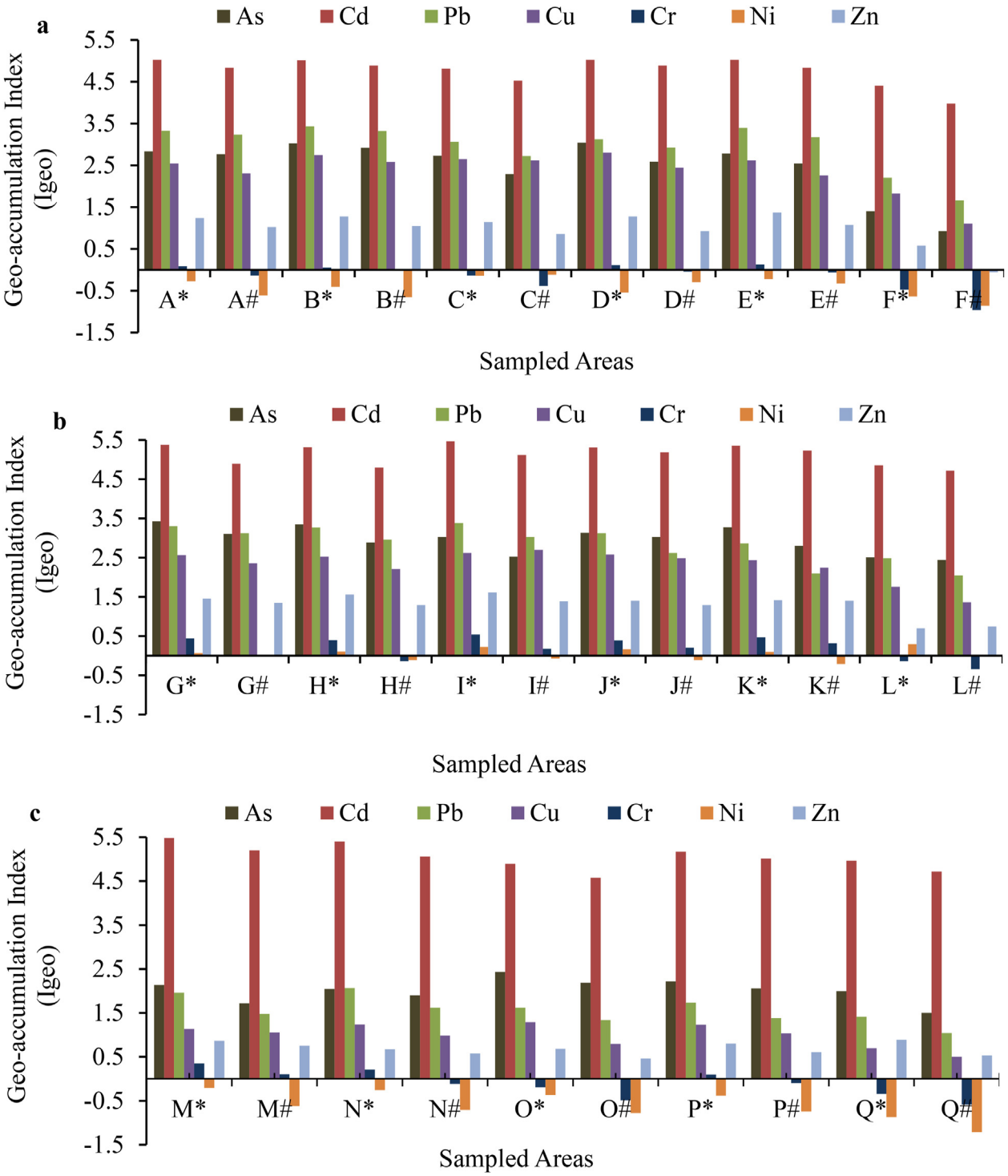

Figure 5. Geo-accumulation Index (I_{geo}) assessment of the topsoil of the study locations. a- I_{geo} for Osogbo site, b- I_{geo} for Ibadan site, and c-f- I_{geo} for Ile-Ife site (* = top soil, # = sub soil).

(Figure 5a). The results further showed a strong pollution of the location due to Pb contribution, with $3 < I_{geo} < 4$ and an extreme pollution as a result of the level of Cd in the soil samples, with I_{geo} value in the range of $4 < I_{geo} < 5$. Similar results were observed for the dump site of the used-electronic market at Ibadan, except that the area was strongly polluted by As (Figure 5b). However, for the Ile-Ife location, only Cd showed similar pollution level with the other locations while Cu, As and Pb presented a moderate pollution effect (Figure 5c). The results affirmed that the study locations were significantly polluted with potentially toxic metals (Cd, Pb, As and Cu), thereby posing serious danger to the health and lives of the residents around the said locations. Although, Ile-Ife location in only extremely polluted with Cd, it is still a cause for concern because of the harmful health effects of Cd on man and other living organisms in the environment as well as the possibility of the metals entering aquatic habitat when washed into water bodies through runoff. The general order of pollution caused by potentially toxic metals as assessed through the geo-accumulation index is Cd > As > Pb > Cu > Zn > Cr ≈ Ni.

3.3.2. Potential ecological risk index

The sensitivity of different biological communities, plants, animals and ecosystem of ecological values, to hazardous substances are assessed with potential ecological risk index (Islam et al., 2015; Li et al., 2014; Maanan et al., 2015; Olawoyin et al., 2012; Qing et al., 2015; Isimekhai et al., 2017). As shown in Table 3, the overall potential ecological risk index for the metals (PERI) evaluated in this study indicates an extremely high level of potential ecological risk (PERI >600) at all the studied locations which can be associated majorly to Cd, As, Pb and Cu in both topsoil and subsoil. The results for the individual metal potential ecological risk index (E^i_f) show an extremely high level of potential ecological risk for Cd at all sampling sites in all the locations studied with E^i_f >320 for both topsoil and subsoil. As, Pb, Cu and Ni exhibited extremely high ecological risk at the primitive recycling factory environment and at the used-electronics market's dumping sites for all the topsoil samples collected and only two subsoil samples demonstrated high ecological risk for the metals with $160 \leq E^i_f < 320$. Cr and Zn show

Table 3. Ecological Risk assessment for the Study Locations.

	As	Cd	Pb	Cu	Cr	Ni	Zn	
	Individual Risk Factor (Er)							PERI
Osogbo								
A*	606.55	2914.41	610.30	642.11	50.67	123.16	29.48	4976.67
A#	566.99	2403.41	556.33	509.20	40.56	87.55	23.69	4187.74
B*	736.96	2881.42	680.39	785.98	48.96	107.49	30.46	5271.66
B#	664.88	2552.84	609.42	668.54	46.18	83.79	24.29	4649.95
C*	547.89	2369.43	470.45	712.49	40.56	140.20	26.66	4307.67
C#	354.16	1770.14	334.08	692.45	31.69	143.51	20.09	3346.12
D*	748.90	2912.84	498.68	831.75	51.80	93.62	30.47	5168.04
D#	474.31	2548.44	410.70	580.82	44.47	119.97	21.52	4200.22
E*	578.69	2915.97	653.66	691.56	52.71	129.20	33.57	5055.36
E#	454.72	2404.41	523.02	482.45	43.70	116.67	24.96	4049.93
F*	145.19	1578.06	198.91	313.04	28.77	85.57	15.20	2364.75
F#	90.09	1023.70	115.30	152.78	17.73	68.51	8.03	1476.14
Ibadan								
G*	1036.77	3604.07	491.76	614.13	70.64	314.97	24.02	6156.35
G#	748.60	2226.54	413.77	498.81	45.18	299.72	21.62	4254.25
H*	957.34	3397.53	477.46	591.89	67.30	326.49	26.65	5844.66
H#	603.77	2013.46	350.79	431.22	39.52	263.15	20.35	3722.26
I*	692.75	3939.51	535.49	646.01	77.95	368.36	28.11	6288.18
I#	420.77	2788.77	374.00	699.95	54.15	274.80	22.46	4634.89
J*	770.94	3364.94	413.66	621.49	67.01	348.43	22.82	5609.29
J#	692.67	2965.31	248.45	568.32	55.69	262.91	20.46	4813.80
K*	890.58	3523.09	316.75	539.48	72.30	324.34	23.08	5689.61
K#	554.46	3101.48	147.73	444.94	62.43	238.26	22.80	4572.11
L*	411.93	2140.00	218.73	274.12	39.45	394.99	11.29	3490.51
L#	386.05	1867.41	140.07	183.69	32.27	295.12	11.83	2916.44
Ile-Ife								
M*	220.66	4061.75	142.18	110.35	64.90	50.64	27.24	4677.72
M#	145.04	3052.38	87.47	101.37	50.63	33.63	24.30	3494.81
N*	201.55	3742.38	157.82	121.80	56.41	48.38	22.45	4350.79
N#	174.88	2665.00	100.83	94.45	40.83	30.81	20.41	3127.21
O*	297.92	2251.38	100.94	128.42	37.74	43.28	22.73	2882.41
O#	233.00	1645.00	75.96	78.49	28.09	28.69	18.12	2107.35
P*	239.77	2976.13	113.26	121.17	50.59	42.56	25.53	3569.00
P#	204.17	2537.63	79.88	99.63	41.57	29.74	20.96	3013.58
Q*	192.09	2415.63	82.12	70.65	32.45	26.17	27.84	2846.95
Q#	117.08	1888.50	56.90	58.53	25.56	18.54	19.43	2184.53

* Topsoil
# Subsoil.

Table 4. Health risk assessment of the topsoil samples of the study locations.

Metals	Non-cancer Risk								Cancer Risk	
	HQIng		HQInh		HQDermal		HI		RI	
	Children	Adults	Children	Adults	Children	Adults	Children	Adults	Children	Adults
Osogbo										
As	**5.42E+00**	5.81E-01	1.52E-04	8.55E-05	3.70E-02	5.37E-03	**5.46E+00**	5.87E-01	**2.46E-03**	**2.64E-04**
Cd	8.39E-01	8.99E-02	2.34E-05	1.32E-05	9.40E-02	1.36E-02	9.33E-01	1.04E-01	1.48E-07	8.33E-08
Pb	**2.90E+00**	3.11E-01	8.07E-05	4.55E-05	5.42E-02	7.85E-03	**2.96E+00**	3.19E-01	8.64E-05	9.27E-06
Cu	3.13E-01	3.35E-02	8.70E-06	4.90E-06	2.92E-03	4.23E-04	3.16E-01	3.39E-02	-	-
Cr	6.07E-01	6.50E-02	1.78E-03	1.00E-03	8.49E-02	1.23E-02	6.93E-01	7.83E-02	**1.01E-03**	**1.52E-04**
Ni	4.79E-02	5.13E-03	1.30E-06	7.32E-07	4.96E-04	7.19E-05	4.84E-02	5.20E-03	2.25E-08	1.27E-08
Zn	2.15E-02	2.30E-03	6.01E-07	3.39E-07	3.01E-04	4.36E-05	2.18E-02	2.35E-03	-	-
Ibadan										
As	**7.11E+00**	5.02E-01	1.99E-04	1.12E-04	4.86E-02	7.04E-03	**7.16E+00**	5.09E-01	**3.22E-03**	**2.30E-04**
Cd	**1.15E+00**	1.23E-01	3.21E-05	1.81E-05	1.29E-01	1.86E-02	**1.28E+00**	1.42E-01	2.02E-07	1.14E-07
Pb	**2.47E+00**	2.64E-01	6.86E-05	3.87E-05	4.61E-02	6.67E-03	**2.51E+00**	2.71E-01	7.34E-05	7.87E-06
Cu	2.50E-01	2.68E-02	6.96E-06	3.92E-06	2.34E-03	3.38E-04	2.53E-01	2.72E-02	-	-
Cr	8.33E-01	8.93E-02	2.44E-03	1.38E-03	1.17E-01	1.69E-02	9.53E-01	1.08E-01	**1.39E-03**	**2.21E-04**
Ni	7.66E-02	8.21E-03	2.08E-06	1.17E-06	7.94E-04	1.15E-04	7.74E-02	8.32E-03	3.60E-08	2.03E-08
Zn	2.45E-02	2.62E-03	6.84E-07	3.86E-07	3.43E-04	4.96E-05	2.48E-02	2.67E-03	-	-
Ile-Ife										
As	**2.66E+00**	3.32E-01	7.44E-05	4.20E-05	1.82E-02	2.64E-03	**2.68E+00**	3.35E-01	**1.21E-03**	**1.51E-04**
Cd	**1.05E+00**	1.13E-01	2.94E-05	1.66E-05	1.18E-01	1.71E-02	**1.17E+00**	1.30E-01	1.85E-07	1.05E-07
Pb	6.53E-01	7.00E-02	1.81E-05	1.02E-05	1.22E-02	1.77E-03	6.65E-01	7.18E-02	1.94E-05	2.08E-06
Cu	6.75E-02	7.23E-03	1.88E-06	1.06E-06	6.30E-04	9.12E-05	6.81E-02	7.32E-03	-	-
Cr	6.08E-01	6.51E-02	1.78E-03	1.00E-03	8.51E-02	1.23E-02	6.95E-01	7.85E-02	**1.02E-03**	**1.48E-04**
Ni	4.41E-02	4.72E-03	1.20E-06	6.74E-07	4.57E-04	6.62E-05	4.45E-02	4.79E-03	2.07E-08	1.17E-08
Zn	1.34E-02	1.43E-03	3.73E-07	2.10E-07	1.87E-04	2.71E-05	1.35E-02	1.46E-03	-	-

Bolded values are those above the recommended values for HQ and HI.

between low and moderate ecological risk with $15 \leq E^{i}_{f} < 80$ for all the samples from the three locations. As, Pb and Cu showed considerable to high ecological risk for all the samples from the Ile-Ife location for both topsoil and subsoil with $80 \leq E^{i}_{f} < 320$. The ecological risk posed by the potentially toxic metals to the studied locations are in the order of Cd > Cu > As > Pb > Ni > Cr > Zn for the Osogbo location, Cd > As > Cu > Pb > Ni > Cr > Zn for the Ibadan location and Cd > As > Pb > Cu > Ni > Cr > Zn for the Ile-Ife location. PERI is used for quantitative expression of the degree of pollution caused by potentially toxic metals in soil (Chen et al., 2015; Wu et al., 2015). The results obtained stressed the risk of human exposure to such environments, proactive measures should therefore be taken to arrest further pollution of the environment.

3.4. Human health risks assessment

The potential human health risks that may ensue as a result of exposure to the topsoil of the studied locations were evaluated and the results are presented in Table 4. Considering the three routes through which potentially toxic metals can enter the human body from the environment, the results obtained for the human health risk assessment showed that the risk posed through each route follows the order: ingestion > dermal contact > inhalation. Generally, for all the metals analyzed, dermal contact and inhalation exposure pathways contributed insignificantly to both carcinogenic and non-carcinogenic health risks for both adults and children. While ingestion exposure route contributed a minimum of 87 % and 83% respectively for children and adults in terms of the non-carcinogenic health risk ($HQ_{ing} \geq 87$ % of HI for children, $HQ_{ing} \geq 83$ % of HI for adults), a minimum of 89% and 65% respectively in terms of carcinogenic health risk for children and adults respectively (RIing $\geq$89% of RI_{Total} for children, $RI_{ing} \geq 65\%$ of RI_{Total} for adults). This suggests that ingestion is the major route of exposure of man to both carcinogenic and non-carcinogenic health risks from the metals in the three studied locations. This observation is consistent with the findings of other researches done in other parts of the world (Chabukdhara and Nema, 2013; Wei et al., 2015; Qing et al., 2015; Wu et al., 2018; Li et al., 2019). Considering the fact that only metal with HI > 1 poses a non-carcinogenic health threat to humans, the results show that generally, the metals individually show no non-carcinogenic health risk to adults. However, the results further revealed that As and Pb for Osogbo location, As, Cd and Pb for Ibadan location, and As and Cd for Ile-Ife location, pose serious non-cancer health threats to children around the studied location. Besides, there is still a need for concern about Cd at the Osogbo location and Cr at the Ibadan location with HI values in the range of $0.93 \leq HI < 1$.

The carcinogenic health risk for residents around the three studied locations requires adequate attention for both children and adults. While the risk is negligible based on the levels of Cd and Ni ($RI < 10^{-6}$), it is only tolerable with respect to Pb ($0^{-6} < RI < 10^{-}4$) but shows a possibility of causing cancer development with respect to As and Cr ($RI > 10^{-4}$), in both children and adults. However, the risk is higher in children probably due to the peculiarity of their physiology coupled with their developmental stages behaviors which lead to higher levels of exposure.

4. Conclusion

The concentration of potentially toxic metals emanating from wrong handling of e-waste, their pollution, and health risks had been systematically evaluated in this study. The impact of three anthropogenic activities that introduce e-wastes into the environment was investigated, including primitive e-waste recycling, unguarded dumping in a used-electronics market, and a typical personal/community indiscriminate disposal of non-functional electronics and electrical gadgets into the immediate environment. The results of the levels of the potentially toxic metals in study locations confirmed that there were gross enrichments of

the local soil with metals due to e-wastes-related activities. The elevated level of the contamination factor ($3 < C_f \leq 166$), of the soil samples from the three studied locations, though represented different anthropogenic activities tied to e-wastes, indicated that the soils of the area have been severely contaminated by potentially toxic metals thereby posing danger to the inhabitants of the area and beyond. The results for the individual metal potential ecological risk index (E^i_f) showed an extremely high level of potential ecological risk for Cd at all sampling sites in all the locations studied with $E^i_f > 320$ for both topsoil and subsoil. As, Pb, Cu and Ni exhibited extreme high ecological risk at the primitive recycling factory environment and at the used-electronics market's dumping sites for all the topsoil samples. The results obtained for the human health risk assessment showed that dermal contact and inhalation exposure pathways contributed insignificantly to both carcinogenic and non-carcinogenic health risks for both adults and children. While ingestion exposure route contributed a minimum of 87 % and 83% respectively for children and adults in terms of the non-carcinogenic health risk ($HQ_{ing} \geq$ 87 % of HI for children, $HQ_{ing} \geq$ 83 % of HI for adults), a minimum of 89% and 65% respectively in terms of carcinogenic health risk for children and adults respectively (RIing $\geq$89% of RI_{Total} for children, $RI_{ing} \geq$ 65% of RI_{Total} for adults). This suggests that ingestion is the major route of exposure of man to both carcinogenic and non-carcinogenic health risks from the potentially toxic metals in the three studied locations. The carcinogenic health risk for residents around the three studied locations indicates a need for necessary attention for both children and adults. While the risk is negligible based on the levels of Cd and Ni ($RI < 10^{-6}$), it is only tolerable with respect to Pb ($0^{-6} < RI < 10^{-}4$) but shows a possibility of causing cancer development with respect to As and Cr ($RI > 10^{-4}$), in both children and adults. Considering the peculiarity of their physiology coupled with their developmental stages behaviors that leads to higher levels of exposure, the children are faced with a higher health risk than adults in the vicinity of the studied locations. The obtained results from this study stressed the risk that the potentially toxic metals in the studied locations pose to the human health and the ecosystem. Therefore, priority should be given to ecological and health protection of areas where similar activities are taking place regularly.

Declarations

Author contribution statement

Adeniyi Abiodun Adenuga: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials; Wrote the paper.

Olufemi David Amos: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Oluwatobi Deborah Olajide: Performed the experiments; Analyzed and interpreted the data; Contributed reagents.

Adebayo Oluwole Eludoyin: Analyzed and interpreted the data; Analysis tools or data; Wrote the paper.

Oluwatope Olaniyi Idowu: Performed the experiments.

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The authors declare no conflict of interest.

Additional information

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