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Toxicity characterization of waste mobile phone plastics

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ABSTRACT

Waste plastic housing units (*N* = 60) of mobile phones (of different models, and brands), were collected and analyzed for lead, cadmium, nickel and silver using atomic absorption spectrophotometry after acid digestion using a 1:1 mixture of H_2SO_4 and HNO_3. The mean (±S.D.) and range of the results are 58.3 ± 50.4 mg/kg (5.0–340 mg/kg) for Pb, 69.9 ± 145 mg/kg (4.6–1005 mg/kg) for Cd, 432 ± 1905 mg/kg (5.0–11,000 mg/kg) for Ni, and 403 ± 1888 mg/kg (5.0–12,500 mg/kg) for Ag. Approximately 90% of the results for the various metals were ≤100 mg/kg. Results greater than 300 mg/kg were generally less than 7% for each metal and could be attributed to exogenous contamination of the samples. These results suggest that there may not be any immediate danger from end-of-life (EoL) mobile phone plastic housing if appropriately treated/managed. However, considering the large quantities generated and the present low-end management practices in most developing countries, such as open burning, there appears a genuine concern over the potential for environmental pollution and toxicity to man and the ecology.

1. Introduction

Electrical and electronic products continue to revolutionize communication, entertainment, transportation, education, and healthcare around the world. There is no sign that this revolution will abate soon. Technical innovation will continue to be a cornerstone of social progress and advanced electronics are leading the way [1]. Mobile telephone, today an indispensable service facilitating everyday life, has experienced a tremendous increase in penetration since the implementation of the innovative Global System for Mobile Communication (GSM) standard in the early 1990's [2,3]. Concern over the negative impacts associated with the production, use and end-of-life (EoL) of cellular telephones is particularly high due to large production volumes and characteristically short time scale of technological and stylistic obsolescence [4,5]. Cellular phones contain a large number of hazardous substances which can pollute the air when burned and leach into soil and drinking water when buried in landfills. These toxic substances include arsenic, lead, cadmium, copper, nickel, etc. [6–9].

From computers and cell phones to televisions and microwaves-design-friendly, durable, lightweight, affordable plastics have helped revolutionalize the electrical and electronic equipment [10]. Plastics can be specially tailored to the demands of electrical and electronic appliances, thereby minimizing waste [10]. Mobile phone manufacturers have made innovative progress at designing recyclable plastic products for the electrical and electronic equipment (EEE) industry in order to meet with the European Unions' Waste Electrical and Electronics Equipment (WEEE Directive) mandated recovery rate of 75 and 65% recycling for EoL EEE. While the amount of plastics in electronics varies substantially, by product – ranging from very small amounts to more than half of the material composition of some mobile phones – the average amount of plastics in the overall electronics stream is quite small [10]. In the case of mobile phone, the plastic housing represents between 15 and 55% of the total weight, without battery [5,11]. Elements such as lead, cadmium, chromium, mercury, bromine, tin and antimony are or have been added to polymers as pigments, fillers, UV stabilizers, and flame retardants. Typically, these materials are added as compounds which often do not chemically bond with molecules of plastic but rather create a suspension in the solid plastic polymer [12].

There has been a phenomenal growth in the information and communication technologies (ICTs) sector in Nigeria since 2001. Presently a greater number of Nigerians have access to mobile telephone and mobile phone is now playing a huge role in the development of the nation's economy (Fig. 1). In fact the mobile telephone has emerged as an integral part of the culture and life of Nigerians. Technical and aesthetic obsolescence of mobile phones are high in Nigeria. This is because a significant number of mobile phones in use are second-hand phones [13]. A situation where a new product in the market has a nicer look or more fashionable design from the point of view of the consumer (aesthetic obsolescence) results in consumers replacing

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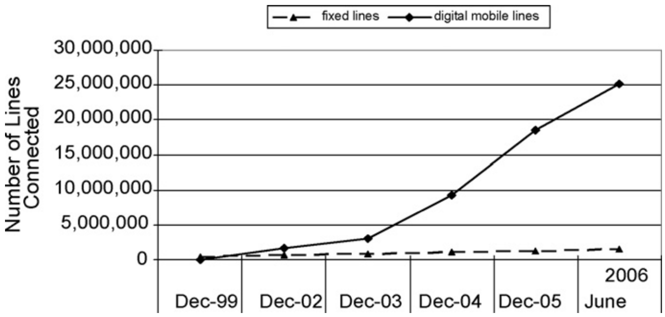

Fig. 1. Progress in mobile telecommunication in Nigeria.

the plastic housing of their mobile phones to make them look "new".

Concerns over toxic metals contents of plastic materials have led to studies at finding rapid, sensitive and reliable methods and instruments for such analysis [12,14,15]. Several testing methods have been adopted in assessing the toxicity of electronic wastes (and other solid waste materials) and in regulating their disposal or EoL management. These include the toxicity characteristics leaching procedure (TCLP), the synthetic precipitation leaching procedure (SPLP), the waste extraction test (WET) and the Total's test (results compared with the total threshold limit concentrations, TTLC threshold values). The TCLP and the SPLP are the leaching tests most commonly used by the US EPA in waste management decision-making. The WET and Total's test were established by the California Department of Toxic Substances Control (DTSC). The TCLP and WET procedures are designed to simulate landfill conditions while the SPLP is an acid rainfall test. The Totals test is an acid digestion procedure that aims at providing information on the elemental composition of solid waste materials.

This paper reports the result of a study to examine the heavy metal (Pb, Cd, Ni, and Ag) levels of waste plastic housing of mobile phones. The objective of this research was to determine the heavy metal levels of a selected component (plastic) of discarded/obsolete mobile phones as "discarded" electronic waste items and not necessarily the inherent metal levels of the plastic materials. This became necessary considering the large quantities of plastic housing units generated and the various low-end management practices for these and other waste materials from the information communications and technology sector in Nigeria. Such waste materials are routinely burned openly, disposed into surface waters or with municipal solid waste [16].

2. Materials and methods

2.1. Sample history/collection

The sixty (60) obsolete mobile phones of fifteen (15) different brands used in this study were collected mainly from mobile phone repairers at the famous computer village in Lagos Southeastern Nigeria. Few samples were collected in Aba, Southeastern Nigeria. Some of the collected mobile phones were partially disassembled phones. The components and modules of such phones have been used in repairing/refurbishing activities. It was observed during sampling that the artisans involved in the repair/refurbishing business pack together the obsolete phones, disassembled parts and other mobile phone components/accessories such as the printed wiring board (PWB), liquid crystal display (LCD) screen, battery (NiMH, Li-ion and Li polymer), etc., and their working tools/materials (such as solder) in their tools bag. Our survey during sampling revealed that as much as 45 obsolete (partially disassembled) phones could be obtained from one mobile phone repairer at the Lagos Computer Village. This is an indication of the extent of waste generation by the IT sector in Nigeria. Mobile phone housing units used in a wide variety of mobile phone models made by various manufacturers and in different countries were included in the samples. Detailed history of each of the phones could not be obtained (e.g., age, year of manufacture, imported new or used, etc.). The samples were transported to the laboratory, dismantled and the sample details such as brand name, model, country of production, serial number, and the IMEI number were recorded. The International Mobile Equipment Identity (IMEI) number enables one-to-one identification of mobile phone [4]. Three to eleven samples were collected for each of the nine different brands whereas single samples were collected for about six different brands. The brands of mobile phone used in this study are: Alcatel, Bird, Bosch, GSM, LG, Motorola, Nokia, Panasonic, Philips, Saegem, Samsung, Siemens, Sony Ericsson, Toshiba, and Trium.

2.2. Sample preparation

The mobile phones were partially disassembled using stainless steel screw-drivers and pliers, and then separated into the major components—PWB, LCD and plastic housing. The plastic samples were first covered with a clean cloth (for each sample) for protection and to avoid cross-contamination and then crushed/weakened by the use of a standard hammer before size reduction by cutting using a stainless steel scissors. The samples were analyzed "as is" without washing in order to access their pollution index as "discarded components". In some cases the mobile phones were either too old for their models to be identified/deciphered or require 'switching on' in order to access the model. For such phones, other identification numbers/letters underneath the battery compartment were used for identification.

2.3. Sample analysis

The samples were digested using a 1:1 mixture of H_2SO_4 (98%):HNO_3 (70%) (total 10 mL per 1 g sample). The samples were digested up to 120 °C and then heated to near dryness. The digest was resolubilized with 10 mL of deionized water and filtered and brought to 50 mL volume with deionized water. This was subsequently analyzed for Pb, Cd, Ni, and Ag by atomic absorption spectroscopy (UNICAM SOLAAR 32). Quality assurance/quality control measures (duplicate analysis, metal spikes, and blanks) were carried out to ensure reliability of results. All glass and plastic ware were cleaned prior to use by soaking in 5% nitric acid overnight, rinsing with water and storing clean. All reagents (H_2SO_4, HNO_3, and deionized water) were of analytical grade. Blanks were introduced with 20% insertion rate.

Chemical analysis of e-waste presents challenges because of the physical nature of the devices (size and composition), and the potential heterogeneity within devices and between devices [17]. To check the heterogeneity of the samples, between sample and within sample replicate studies were carried out. One brand was selected and used in the within-sample replicated study ($N = 10$), whereas three different brands were used in the between sample replicate study.

3. Results and discussion

3.1. Summary of metal concentrations in samples

Result of the within-sample replicated gave a precision (calculated as coefficient of variation) of 31% for Ni, 59% for Pb, 33% for Ag, and 40% for Cd. The between-sample replicate study gave precision

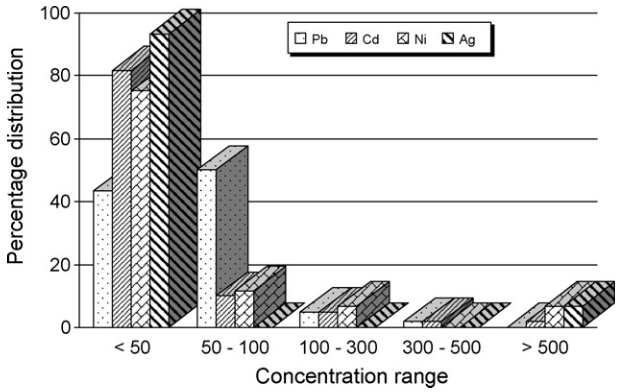

Fig. 2. Percentage distribution of the result according to different concentration ranges.

of 12–33% for Pb; 8–19% for Cd; 20–43% for Ni; 22–43% for Ag. The variation in the result of the replicate analysis and some high values in the calculated precision may have resulted from unequal distribution of the metals in the solid plastic polymer matrix or from contaminants on the surface of the samples considering that the samples were analyzed "unwashed". Results of replicate analysis of metals in electronic devices reported a precision (expressed as coefficient of variation) of 27% for Cd, 33% for Pb, 67% for Ni, and 11% for Ag [17].

The means and ranges of trace metal concentrations of the plastic housing units according to brand are shown in Table 1. The mean values according to brand varies from 36.3 ± 13.2 mg/kg in Samsung to 123 ± 188 mg/kg in Bird for Pb; 32.0 ± 8.5 mg/kg in Siemens to 157 ± 307 mg/kg in Nokia for Cd; 23.8 ± 12.5 mg/kg in Samsung to 2775 ± 5483 mg/kg in Sony Ericsson for Ni; from 7.5 ± 2.7 mg/kg in Siemens to 370 ± 826 mg/kg in Nokia for Ag. The result had a positively skewed distribution as a result of few outliers, usually less than 7% of the data set for all metals analyzed. Correlation study of the results indicated no significant positive relationship between the metal pairs. The Pb levels in the samples appear to be better distributed as compared to the results for the other metals. Similarly, there are but only one of the Pb results that exceeded 300 mg/kg as compared to 2 mg/kg for Cd, and four samples each for Ni and Ag.

The overall mean (±S.D.) concentrations for Pb, Cd, Ni, and Ag in the samples are 58.3 ± 50.4, 69.9 ± 145, 432 ± 1904, and 403 ± 1888 mg/kg, respectively (Table 2). The very high standard deviation values of our result indicate the heterogeneous nature of the heavy metals distribution in the samples. Much of the heterogeneous data distribution could be attributed to exogenous contamination of the samples.

3.2. Distribution of metals in the samples

The results indicates that about 80, 75, and 90% of the samples studied contained less than 50 mg/kg of Cd, Ni, and Ag, respectively (Fig. 2). However, for Pb, only about 43% of the results were less than 50 mg/kg. In general approximately 90% of the samples studied contained ≤100 mg/kg for each of the metals analyzed. Fig. 2 depicts the distribution of the heavy metals levels observed in the samples according to five concentration ranges. Fig. 3 indicate that the higher values of metals obtained in some of the samples especially for values greater than 300 mg/kg may have resulted from external contamination considering that the samples were analyzed 'unwashed'. Contacts with solder and battery, and depositions from solder fumes during repair activities may contribute to the high levels of metals observed in some of the samples. Samples analyzed with values greater than 300 mg/kg for the four metals

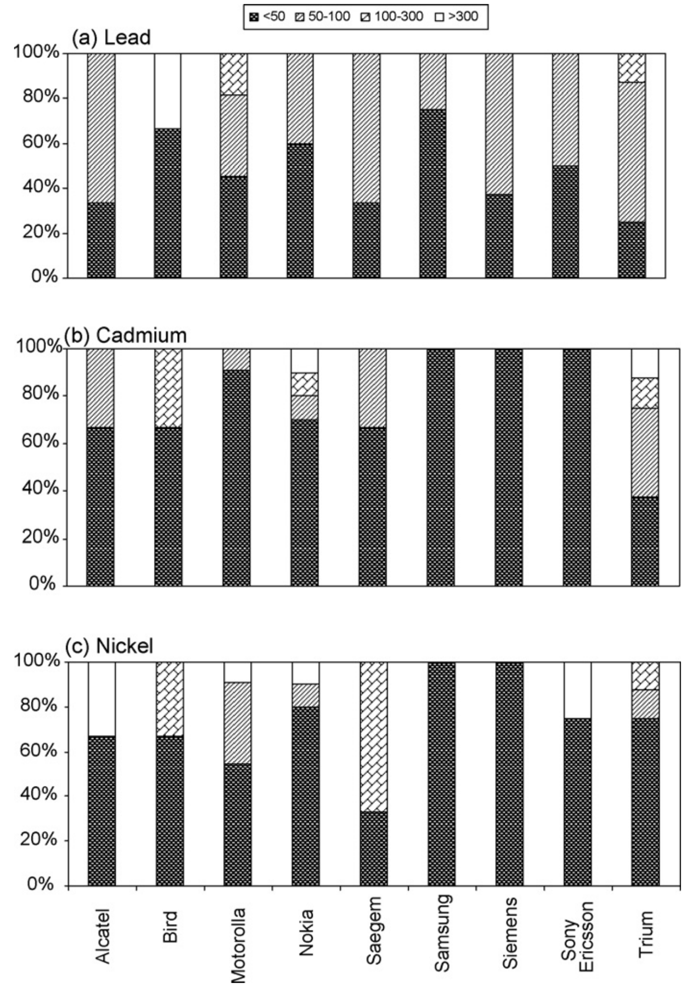

Fig. 3. Distribution of metals in the samples according to brand.

determined were generally less than 7% (for each metal). Only two samples contained Pb levels in excess of 200 mg/kg; three samples in excess of 200 mgCd/kg; four samples in excess of 200 mgAg/kg; seven samples exceeded 200 mgNi/kg. The percentage distributions of Pb, Cd, and Ni in the samples grouped according to brand are shown in Fig. 3a–c. The result of analysis of several types of electrical and electronic plastics (and plastic mix) from various sources reported Ni levels ranging from less than 1 to 110 mg/kg; Cd levels of 13–110 mg/kg, and Pb levels of 170–1010 mg/kg [18 cited in 1]. Metal levels reported in electrical and electronic plastic materials and in mobile phones (entire device-plastics, PWB, etc.) are presented in Table 3.

3.3. Comparison with established regulations and the TTLC threshold

There have been attempts at regulating the heavy metal levels in plastics. The first regulation to specifically target heavy metals in plastics was introduced in the mid-1990s by the European Community. The European Community "Packaging Directive"—EC Directive 94/62/EEC, regulates the total amount of metals such as Cd, Cr, Hg, and Pb in plastic materials to less than 100 mg/kg [12]. Another EU Directive (91/338/EC) sets the maximum allowable concentration of cadmium in plastics used for consumer goods at 100 mg/kg [12]. Similarly, the EU Directive on the Restriction of Hazardous Substances, RoHS (Directive 2002/95/EC) which became effective

Table 1
Heavy metal concentrations (mean ± S.D. and range) of plastic housing units of mobile phones according to brand (mg/kg)

Brand	*N*	Pb	Cd	Ni	Ag
Alcatel	3	46.7 ± 15.3 30.0–60.0	48.1 ± 12.6 39.2–62.5	640 ± 1070 5.0–1875	11.7 ± 7.6 5.0–20.0
Bird	3	123 ± 188 5.0–340	66.8 ± 71.6 24.5–149	98.3 ± 140 15.0–260	8.3 ± 2.9 5.0–10.0
Bosch	1	55.0	46.5	20.0	12,500
GSM	1	55.0	40.9	35.0	5.0
LG	1	75.0	42.8	5.0	5.0
Motorola	11	65.0 ± 59.0 5.0–210	36.3 ± 19.6 4.6–85.4	101 ± 216.4 5.0–750	9.1 ± 3.0 5.0–15.0
Nokia	10	43.5 ± 25.9 15.0–95.0	157 ± 307 25.7–1005	1030 ± 3152 5.0–10,000	370 ± 826 5.0–2500
Panasonic	1	60.0	43.1	40.0	7500
Philips	1	75.0	41.9	5	25.0
Saegem	3	58.3 ± 34.0 20.0–85.0	43.6 ± 11.6 31.5–54.7	153 ± 98.3 40.0–215	8.3 ± 2.9 5.0–10.0
Samsung	4	36.3 ± 13.2 25–55	35.1 ± 6.3 26.6–40.1	23.8 ± 12.5 5.0–30.0	8.8 ± 2.5 5.0–10.0
Siemens	8	56.3 ± 27.7 25.0–95.0	32.0 ± 8.5 19.9–45.1	24.4 ± 9.0 10.0–35.0	7.5 ± 2.7 5.0–10.0
Sony Ericsson	4	47.5 ± 17.1 25.0–65.0	37.3 ± 4.7 32.7–41.8	2775 ± 5483 30.0–11,000	8.8 ± 4.8 5.0–15.0
Toshiba	1	60.0	39.5	30.0	5.0
Trium	8	62.5 ± 32.4 5.0–110	121 ± 184 36.6–573	41.3 ± 29.1 15.0–105	13.8 ± 10.9 5.0–35.0

Table 2
Summary of heavy metal results of the study (mg/kg)

Metal	Mean ± S.D.	TTLC	*N* > TTLC	Range
Pb	58.3 ± 50.4	1000	Nil	5.0–340
Cd	69.9 ± 145	100	5	4.6–1005
Ni	432 ± 1905	2000	2	5.0–11,000
Ag	403 ± 1888	500	4	5.0–12,500

N > TTLC = number of samples greater than the respective TTLC threshold.

July 2006 calls on manufacturers to be environmentally responsible and to not use in their products any homogenous material, parts or subassemblies that contains a maximum values of 0.1% by weight for Pb, Hg, Cr^{6+}, polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE), and 0.01% by weight in homogenous materials for Cd. In this directive, homogenous material is defined as "a material that cannot be mechanically disjointed into different materials" and can be understood as "of uniform composition throughout" [19]. This directive aims at protecting human health and the environment by reducing these harmful substances at source. The lead results were generally less than 1000 mg/kg, the maximum allowable concentration of Pb allowable in homogenous components of electronic products by the RoHS Directive. However, only about 8% samples contained Cd in excess of 100 mg/kg, the maximum allowable concentration of Cd in plastics by the RoHS Directive.

Table 3
Metal levels reported in electrical and electronic plastic wastes and in mobile phones

	Metal levels (mg/kg)				Reference
	Pb	Cd	Ni	Ag	
Mixed plastic residue-1	249	–	–	–	Matsuto et al. [28]
Mixed plastic residue-2	254	–	–	–	Matsuto et al. [28]
Plastic cabinet (TV)	2250	51.2	–	–	Matsuto et al. [28]
Plastic dust	1,130	–	–	–	Matsuto et al. [28]
Mobile phone*	10,140	2.93	9247	65.9	Lincoln et al. [29]
E & E plastic mix	170–1,010	13–110	–	–	Vehlow et al. [18]
Cell phone*	4,667	ND-3	1946	235	DTSC [17]
Telephone sets*	2,176	6	1233	78	DTSC [17]

*Analyzed using the TTLC procedure.

Table 4
Total concentration of selected metals determined in mobile phones (mg/kg)

Sample	Cd	Pb	Ni	Ag
Motorola	ND	5958	1862	186
Motorola i1000 plus	2	1514	2630	77
Motorola	3	4656	2059	160
Motorola i1000 plus	ND	5049	954	398
TTLC levels	100	1000	2000	500

Source: DTSC [17].

The Totals test (or TTLC) is a chemical digestion procedure developed by the Department of Toxic Substances Control (CA, United States) to determine the total amount of a specific constituent in a sample material. This requires the chemical digestion of the sample to obtain the soluble and insoluble fractions. The results obtained are then compared with the TTLC threshold values in order to determine whether the sample should be classifies as 'hazardous'.

Compared to the TTLC limit concentrations, five results exceeded the TTLC threshold for Cd (100 mg/kg) while only two results exceeded the threshold for Ni (2000 mg/kg), and these Ni values are about fivefold the threshold value. Four high Ag results were obtained that exceeded the TTLC threshold for Ag. One of these values is approximately 25-fold the TTLC threshold for Ag. This may have resulted from contamination with solder materials considering the replacement of Pb in the tin/lead solder with other elements such as bismuth, silver, and copper. The solder compositions under consideration or presently in use include Sn/Ag/Cu, Sn/Ag, and Sn/Bi/Ag alternatives. However, the Sn/Ag/Cu solder represents the preferred alternative [3,20].

The toxic material contents of mobile phones have necessitated studies into the environmental impact of mobile phones and other electronic devices. An analysis of mobile phones (entire device, plastics, PWB, etc.) using EPA Method 3050B indicates that the Pb content of the samples exceeded the TTLC limit for all samples (Table 4), whereas the levels of Ni exceeded the TTLC for two samples [17]. Toxicity characterization of the same samples using the toxicity characterization leaching procedure (TCLP) indicated that the extractable Pb exceeded the TCLP threshold for Pb (5 mg/L) in three of the samples with an average extractable Pb level of 52 mg/L [17]. Similarly, studies by Townsend et al. have shown that electronic devices, including mobile phones have the potential to leach lead concentrations above the toxicity characterization of 5 mg/L when leached using the TCLP extraction solution. One of the studies reported a mean extractable lead concentration of 52.86 mg/L in 78 cell phones (all of Motorola Model i600) [21] and the other an average extractable Pb concentration of 20 mg/L, with 28 of the 38 cell phone samples exceeding the toxicity characterization limit for Pb [22].

3.4 Implications of improper management

The improper treatment of EoL electrical and electronic equipment can result in a loss of useful materials, which depending on the concentration and state can cause undesirable environmental effects [3]. Issues in the environmentally sound recycling and recovery practices for EoL mobile phones have been extensively discussed [8,9]. Ideally, plastics should be separated at EoL from the other fractions, ground, mixed with a certain percentage of virgin material and used again for the same or similar application. In practice a maximum amount of 20–30% of recycled material is likely [10].

There are potentials for material and energy recovery from waste plastics from electrical and electronic equipment. This has been extensively researched and the technology has been developed [1,11,23,24]. Fisher et al. [1] observed that presently the challenges facing material recovery from plastic waste from EEE "appears to be related to education and infrastructure development than to technology". Infrastructure determines the process method and amounts of waste that can be processed. Collection methodology, sorting and recovery technologies, material recycling processes and disposal methods are the key factors in the comprehensive recycling of e-waste [25]. To meet the demanding rates of the EU Directive on WEEE, plastic parts of EEE have to be designed for high recyclability [11].

The preferred option for plastics from EoL electronics is recycling. Electronic plastics can be used in chemical feedstock recycling processes, as processed engineering fuel, or in energy recovery systems [1,10,26]. Landfilling is the least preferred option. However, Fisher et al. [10] observed that in some countries, this may be the best choice based on local or regional considerations. This is true for Nigeria considering the low-end management practices for such waste materials. Such waste materials are usually burned openly, making it easier for storm run-off to leach such ash and cinder into surface waters used for domestic purposes. The open burning of waste plastics from mobile phones may result in gaseous emissions containing heavy metals, polychlorinated biphenyl (PCB), and dioxins (considering the use of Br as a flame retardant and the use of polyvinyl chloride (PVC) in such plastics) or the release of metals and other toxins into soil or water bodies through leaching of the waste materials or the resulting ash and cinder. Considering the present management practices, landfilling using appropriate landfill technology presents less risk to the environment and man in the short-to-medium terms.

4. Conclusion

The results of the present study showed that the levels of lead, cadmium, nickel and silver in plastic housing units of mobile phones do not constitute significant danger if managed appropriately. However, these e-waste components could pose potential danger to the environment and human health in the developing countries considering the various low-end management practices. Waste incineration and landfilling using appropriate technology are rare in Nigeria and most other developing nations [16]. Low- or moderate-temperature treatment of wastes has the potential to form more toxic by-products than does incineration [27]. As such, the current open burning practices for ICT waste materials may be more dangerous than initially thought. There is an urgent need to introduce a policy for the material/energy recovery from waste plastics from EoL electronics in developing countries as is currently the practice in developed countries following the principles of sustainable development.

It has been observed that efficient collection is perhaps the most significant hurdle to the economic recycling of plastics from EoL electronics—not technology (which has been developed), not contamination (which can be managed by today's technology), and not the intrinsic value of recovered plastics [5,10,24].

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