sciendo

DOI: 10.2478/auoc-2023-0011

Ovidius University Annals of Chemistry Volume 34, Number 2, pp. 83 - 90, 2023

End-of-life mobile phones parts contain toxic metals that make them hazardous, but can also serve as resource reserves for such metals

Bukola Omoyemi ABIODUN[1] and Paschal Okiroro INIAGHE[*2]

[1]*Department of Chemistry, University of Ibadan, Ibadan, Nigeria*
[2]*Department of Chemistry, Federal University Otuoke, Nigeria*

Abstract. In this study, the concentration of some toxic metals in different parts of end-of-life mobile phones was assessed. Twenty end-of-life mobile phones of different brands and countries of origin, which were widely in use up to the year 2011, were collected from phone repair workshops in Lagos, Nigeria. The collected mobile phones were disassembled into the phone screens, printed wiring boards, plastic casings and batteries. Disassembled parts were individually milled and pulverized, and digested using HCl, HNO_3 and H_2O_2. Flame atomic absorption spectrometry was used to quantify some toxic metals (Pb, Cd and Ni) in the digested samples, and the determined concentrations were compared with permissible limits. The average metals concentration in the disassembled parts followed the order: printed wiring boards > batteries > plastic casings > phone screens. The concentrations of Pb and Ni exceeded their toxicity threshold limit concentration in printed wiring boards, while Ni exceeded the limit concentration in batteries. Based on the maximum permissible concentration required by the Restriction of Hazardous Substances (RoHS) Directives, all Cd concentrations were below the limit concentration; Pb and Ni in printed wiring boards exceeded their limit concentrations, while Ni exceeded its permissible concentration in batteries. The results of this study indicate that printed wiring boards and batteries of end-of-life mobile phones are hazardous, and their improper disposal of could cause environmental and health problems. However, considering the very high concentrations of Pb and Ni, these mobile phone parts could serve as resource reserves for these metals.

***Keywords*:** toxic metals; end-of-life mobile phones; printed wiring boards; batteries; toxicity threshold limit concentration; Restriction on Hazardous Substances Directive.

1. Introduction

Mobile phones are multipurpose devices that are now an integral part of man's daily life [1]. They are chiefly used for communications purpose, but can provide other services such as internet access, calculator, cameras, games, e-mailing, etc. [2]. The use of mobile phones has increased significantly in the last two decades [3]. It was projected in 2009 that 4.7 billion mobile phones were subscribed worldwide; majority of which were present in third world countries, and more than half the global population [4]. By 2019, there were over 7 billion active mobile phone subscriptions globally, including 5.4 billion in developing countries [5].

In Nigeria, there has been a phenomenal growth in the information and communication technologies sector. Currently, a larger percentage of Nigerians have access to mobile phones; for instance, Nigeria's teledensity increased from less than 1% in 2001 to about 25% in 2006 [6]. In April 2023, the number of active mobile phone subscribers was 223.6 million, with a teledensity of approximately 117% [7]. Additionally, the introduction of innovative smartphones with better-quality technologies and functionalities such as touchscreens, cameras, music and video players, games, higher random access memory and web browsing features implied that "mobile phones" had rather shortened lifespans, and became obsolete by the original users within a short period of time, even though the latter were still in perfect working conditions [3]. One of the explanations why phone users purchase phones with innovative features much more frequently is because such high-tech phones are considered "fashion icons", which convey the holder's personality [2]. Waste mobile phones thus contribute a major portion to the "electronic waste" stream in terms of number of discarded units [8].

A typical mobile phone is made up of a plastic casing (which sometimes coexist with metal linings/coatings), a wiring board, a screen (liquid crystal display), a battery (usually NiCd or Li-ion), a keyboard and sometimes, an antenna (especially in older models) [9]. Mobile phones also contain several metals and organic chemicals [10]. The toxic, special and precious metals content of mobile phones are required for the proper functioning of the device [3]. On the average, metals reportedly account for 23% of a phone's total weight [11], while plastics make up more almost half the weight [1]. Mobile phones thus have the potential to generate significant environmental impact due to their toxic metallic content [12]. For example, the amount of Cd from a mobile phone battery was reported to be adequate to foul 600,000 litres of water [13]. Worries over the deleterious impacts linked the manufacture, use and end-of-life (EOL) of mobile

* Corresponding author. *E-mail address*: po.iniaghe@gmail.com (Paschal Okiroro Iniaghe)

phones is on the increase; this is predominantly due to huge volumes manufactured, characteristically short obsolesce time and increasing metals content [14, 15]. Although there is an upsurge in the number of skilled artisans involved in repair of used mobile phones which lengthens a phone's lifespan to around 7 years, it is on estimate that between 2001–2006, phone batteries and chargers were replaced biannually, and this increased the total waste generation of these components to roughly 3,000 and 9,500 tonnes respectively [6].

This study was carried out to assess some toxic metals concentrations in EOL mobile phone parts, including the phone screens (PS), printed wiring boards (PWB), plastic casings (PC) and batteries (BT); to compare the concentration of these metals with their maximum permissible concentrations as contained in the Restriction of Hazardous Substances Directive [16] to evaluate their safety upon disposal, as well as understand their potential as resource reserve for metals.

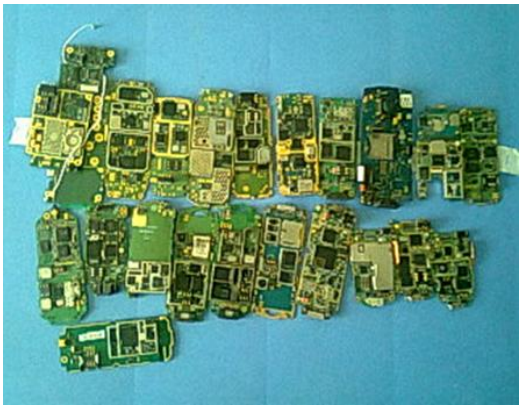
2. Experimental

2.1. Sample description and preparation

Twenty (20) EOL mobile phones of different models, which were in use up to 2011, were obtained from phone dealers in the Computer Village in Lagos State, Nigeria. Extraneous materials like nuts, screws and metal frames were removed. The total weights of the whole phones were recorded. The phones were individually disassembled into the PS, PWB, PC and BT components, respectively (Fig. 1).

The BT components were disassembled using pliers, screwdrivers and hammer, and then separated into the electrode and separators. The electrode components were unwound and size-reduced using stainless scissors, and were subsequently used for analysis. The other individual components of the mobile phones were separately milled using a locally fabricated stainless steel hammer milling machine at the Faculty of Technology, University of Ibadan, Nigeria, and were passed through a 2 mm mesh sieve. Minimization of cross-contamination between samples was done by cleaning the milling machine with dried wood chips, which had been previously determined to be free of the metals of interest. The machine was thereafter inspected for leftover chips, and pressurized air was blown through the machine to ensure that it was completely free of both samples and wood chips. Representative sub-samples for analysis were collected from the milled bulk samples, placed in polythene bags and taken to the laboratory.

a.



b.

c.

d.

Figure 1. Pictorial representation of: (a) EOL mobile phones used in this study; (b) printed wiring boards; (c) plastic casings; (d) batteries.

2.2. Metals extraction and analysis

The EPA SW 846 Method 3050B [17] was used for digestion of different components of the EOL mobile phones as follows: About 1.00 g of each representative sub-sample was weighed and transferred into different digestion vessels. Then, 10 mL of 1:1 HNO_3 was added to each of the samples in the digestion vessel and covered. The samples were heated to 95 $^oC \pm 5\ ^oC$ in a digestion block and refluxed for 10 minutes. The samples were allowed to cool, after which 5 mL of 67% HNO_3 was added. The cover was replaced, and heating was continued for another 30 minutes. The latter step was repeated until brown fumes no longer evolved. 2 mL of deionised water and 3 mL of 30% H_2O_2 were slowly added, and a maximum of 10 mL 30% H_2O_2 was added until the general appearance remained unchanged. Heating was continued at 95 $^oC \pm 5\ ^oC$ for 2 hours. 10 mL of 36.4% HCl was added and covered, and finally heated and refluxed at 95 $^0C \pm 5\ ^0C$ for 15 minutes. The sample digests was filtered and the filtrate was collected in a 100 mL volumetric flask. The filtrate was then made to mark with deionised water.

For the plastic casings, 0.15 g representative sub-sample was weighed into a digestion vessel according to the US CPSC-CH-E1002-08 Test Method [18]. Approximately 5 mL of concentrated HNO_3 was added to the digestion vessel containing the sample. The vessel was covered and heated at 210 ^oC for 30 minutes until effervescence subsided. The sample was then allowed to cool. The digested sample was then quantitatively transferred to a 50 mL volumetric flask and diluted to 50 mL mark with deionised water.

Filtrates from both digestion steps above were analysed for Pb, Cd and Ni by flame atomic absorption spectrometry (Perkin Elmer AAnalyst 200, Germany). The limits of detection of the analysed metals by the measuring instrument were as follows: Pb (0.001 mg L^{-1}), Cd (0.001 mg L^{-1}) and Ni (0.003 mg L^{-1}).

2.3. Quality control measures

All glass and plastic ware were washed before use by soaking in 5% HNO_3 for 12 hours, rinsed with water and stored clean. The reagents used were of analytical grade. Milling tools and surfaces were cautiously cleaned after pulverization of samples to prevent cross-contamination. Procedural blanks were introduced with 20% insertion rate and were used to check for impurities in reagent and method. Samples were analyzed in triplicates to check for precision of the results obtained. The accuracy of the analytical method was validated using the matrix spiked recovery study. In this method, a known quantity of the analyte was added to an already analyzed sample; and all steps taken in analyzing the sample were applied to the spiked sample. The recovery was calculated using the expression:

$$\%\ Recovery = \frac{conc.of\ spiked\ sample\ -\ conc.of\ unspiked\ sample}{conc.of\ the\ spike\ added\ to\ the\ sample}\ x\ 100 \quad (1)$$

3. Results and discussion

3.1. Weight distribution of EOL mobile phones

Table 1 presents the weight of EOL mobile phones and the dismantled components. Out of the 20 mobile phones used in this study, only 50% of them had their batteries available. The average weight distribution of EOL mobile phones showed that Nokia products had the greatest weight, while Motorola products had the least weight. The average weight distribution followed the order: Nokia > Sony Ericsson > Samsung > Sagem > Sendo > Motorola. The phone weights ranged between 47.3 g to 114.8 g, with a mean weight of 80.6 g. The BT and PC components generally represented the largest components of the disassembled EOL mobile phones. The average percent weight distribution (shown in Figure 2) indicated that BT component accounted for 11.1%, 29.5%, 31.4%, 28.5% and 28.6% in Sony Ericsson, Nokia, Samsung, Sagem and Sendo, respectively (no batteries were available in the Motorola products used in this study); while for the PC, the weight percent distribution as a function of the total weight of the mobile phone were 21.9%, 28.1%, 25.3%, 23.9%, 26.3% and 30.8% respectively for Sony Ericsson, Nokia, Samsung, Sagem, Motorola and Sendo (it should be noted that the total weight of PC, PWB, PC and BT components were less than the total weight of each mobile phone; this was due to the fact that during the disassembling process, screws and nuts, which are metallic and relatively heavy, were not included in the weighing process).

Table 1. Weight of EOL mobile phones and their individual dismantled components

Type	Model no.	Country of manufacture	Weight (g)				
			Phone	Screen	Printed wiring board	Plastic casing	Battery
Sony Ericsson	J100i	France	81.8	3.9	13.7	24.2	16.5
Sony Ericsson	S710i	Japan	104.4	6.4	16.5	16.4	NA
Sony Ericsson	P800	France	114.8	26.4	26.5	26.4	NA
Sony Ericsson	T100	Sweden	66.5	4.6	16.3	13.4	23.9
		Mean	**91.8**	**10.3**	**18.3**	**20.1**	**10.2**
Nokia	5210	Hungary	91.7	3.2	15.3	21.2	26.3
Nokia	1210	Hungary	43.5	4.4	14.2	16.5	NA
Nokia	3410i	Germany	68.4	4.4	16.5	23.4	NA
Nokia	8310	Hungary	81.8	2.3	14.3	16.3	23.2
Nokia	3310	Germany	75.9	4.1	16.4	36.5	NA
Nokia	RAE- 3N	Hungary	239.1	24.6	37.4	54.8	39.0
		Mean	**100.1**	**7.2**	**19.0**	**28.1**	**29.5**

Type	Model no.	Country of manufacture	Weight (g)				
			Phone	Screen	Printed wiring board	Plastic casing	Battery
Samsung	SGH-X480	Korea	74.2	6.3	10.6	24.6	22.1
Samsung	SGH-S200	Korea	84.0	6.5	11.9	15.4	25.5
Samsung	SGH-E250	Germany	87.6	6.4	13.7	26.4	23.6
Samsung	SGH-600C	Korea	96.4	3.7	16.6	20.2	36.2
		Mean	**85.6**	**5.7**	**13.2**	**21.7**	**26.9**
Sagem	My 700X	Hungary	82.4	5.7	16.5	23.5	20.4
Sagem	My 3020	China	98.6	5.2	15.7	31.1	26.5
Sagem	My X5-2	Hungary	63.4	6.1	16.2	16.4	NA
		Mean	**81.5**	**5.7**	**16.1**	**23.7**	**23.5**
Motorola	C168	Japan	47.3	5.4	11.2	14.5	NA
Motorola	V220	China	65.1	6.3	16.0	15.1	NA
		Mean	**56.2**	**5.9**	**13.6**	**14.8**	**NA**
Sendo	S360	Korea	68.5	3.5	14.6	21.1	26.5
Overall mean			**80.6**	**6.4**	**15.8**	**21.6**	**23.3**

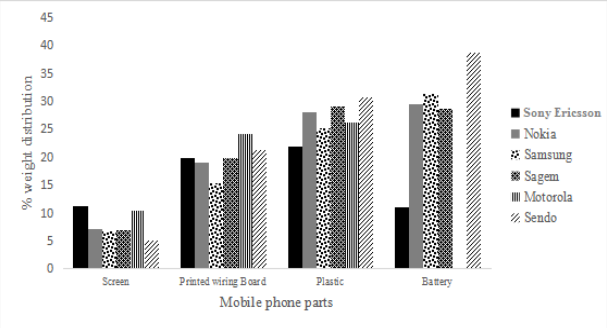


Figure 2. Average weight percentage distribution of EOL mobile phone parts

3.2. Metals concentration in EOL mobile phone components

A summary of the results of metals concentration in the different analysed components of EOL mobile phones are presented in Table 2. The determined concentrations (mean ± standard deviation in parenthesis) ranged from < 0.001 – 2,748.0 (468.4 ± 1,116.9) mg kg^{-1} for Pb, 3.0 – 9.2 (4.91 ± 1.6) mg kg^{-1} for Cd, and 17.8 – 432.4 (86.1 ± 95.0) mg kg^{-1} for Ni in the PS. The concentration of metals analysed in the PS of the mobile phones were generally low for the respective metals except one of the phone screen samples (a German-made Nokia phone), representing 5% of the total mobile phone samples. The PS of this sample had a Pb concentration that exceeded the toxicity threshold limit concentration (TTLC) of 1,000 mg kg^{-1} [19]. The increased Pb concentration in this sample might be because it was one of the first coloured screen mobile phones produced in the first generation network. To corroborate these results, metals concentration ranging from < 0.001 – 187 mg kg^{-1} for Pb, 103 – 877 mg kg^{-1} for Ni and < 0.001–4.70 mg kg^{-1} for Cd in PS of cellular phones were reported by [20].

With the introduction of smart phones which possess touchscreen features, the touchscreen contains a thin layer of indium-tin oxide, which is highly conducting and transparent [21], and this has largely replaced liquid crystal display (LCD) screens. Although this touchscreen is inherently disadvantaged due to the ease with which it breaks when it falls on a hard surface, as well as the high cost of replacement of broken screens, there is still an unprecedentedly high demand for such smartphones, especially in developing countries. The chemical composition of these screens will also pose environmental nuisance since they contain polycyclic aromatic hydrocarbons in solid forms [22]. They also have no reuse option at the moment, and as such, are discarded rather indiscriminately.

The concentration (mean ± standard deviation in parenthesis) of the studied metals in EOL mobile phone PCs ranged from 4.8 – 1,153.5 (232.9 ± 299.6) mg kg^{-1} for Pb, 3.0 – 12.8 (6.0 ± 2.5) mg kg^{-1} for Cd, and 14.3 – 1,820 (294.0 ± 511.3) mg kg^{-1} for Ni. Only one sample (Samsung, made in Korea), representing 5% of the total samples, exceeded the TTLC Pb concentration of 1,000 mg kg^{-1}. The concentration of Cd in all PC samples analysed were all below the 100 mg kg^{-1} Cd TTLC [19]. Similarly, Ni concentrations in the analysed samples were generally less than 500 mg kg^{-1} but two samples exceeded the TTLC limit of 2,000 mg kg^{-1} [19]. The reported concentrations of Pb, Cd and Ni in the plastic components of electrical equipment were 17.4, 5.71 and < 0.001 mg kg^{-1} [23], while a range of 5.0 - 340 mg kg^{-1} of Pb and a mean concentration of 4.6 mg kg^{-1} of Ni in mobile phone plastics were reported by [24]. These results indicate that metals concentrations are generally low in plastic e-waste components.

Table 2. Concentration of toxic metals in various parts of EOL mobile phones

Type	Model No.	Country of manufacture	Metals concentration (mg kg^{-1})											
			Phone screen			Printed wiring boards			Phone plastic casings			Phone batteries		
			Pb	Cd	Ni	Pb	Cd	Ni	Pb	Cd	Ni	Pb	Cd	Ni
Sony Ericsson	J100i	France	<0.001	9.4	47.9	1,875.8	9.4	15,342.2	512.6	5.0	14.3	20.4	9.0	49772.8
Sony Ericsson	S710i	Japan	3.2	12.0	49.4	2,929.0	12.0	58,741.6	4.8	9.3	1,820.0	NA	NA	NA
Sony Ericsson	P800	France	<0.001	8.8	55.4	25,835.8	8.8	17,006.8	44.5	8.3	53.3	NA	NA	NA
Sony Ericsson	T100	Sweden	<0.001	7.4	39.6	27,956.8	7.4	16,810.0	30.0	5.17	197.0	24.6	10.6	16,766
Nokia	5210	Hungary	<0.001	10.6	38.2	24,684.4	10.6	27,470.0	71.8	12.8	86.3	NA	NA	NA
Nokia	1210	Hungary	<0.001	15.0	47	2,282.6	15.0	19,967.0	657.8	4.8	237.2	NA	NA	NA
Nokia	3410i	Germany	2748	10.4	110.9	22,543.2	10.4	27,322.4	20.7	4.3	23.0	NA	NA	NA
Nokia	8310	Hungary	10.8	9.8	216.6	22,179.6	9.8	44,924.8	189.2	5.7	48.7	146.8	8.0	8,706.2
Nokia	3310	Germany	<0.001	16.0	135.4	22,119	16.0	42,541.1	50.7	5.0	17.7	NA	NA	NA

Type	Model No.	Country of manufacture	Metals concentration (mg kg^{-1})											
			Phone screen			Printed wiring boards			Phone plastic casings			Phone batteries		
			Pb	Cd	Ni	Pb	Cd	Ni	Pb	Cd	Ni	Pb	Cd	Ni
Nokia	RAE- 3N	Hungary	2.2	10.8	34.4	27,956.8	10.8	31,518.0	39.2	7.0	24.0	47.6	14.4	34,946
Samsung	SGH-X480	Korea	<0.001	8.8	36.6	24,462.2	8.8	21,582.2	155.5	4.0	456.0	20.6	14.0	10362.6
Samsung	SGH-S200	Korea	<0.001	7.4	19.6	17,331.6	7.4	17,911.8	1,153.5	4.7	186.7	38.6	12.6	11493.8
Samsung	SGH-E250	Germany	<0.001	8.6	20.6	10,524.2	8.6	39,551.6	35.5	3.0	368.7	21	11.0	5,918.6
Samsung	SGH-600C	Korea	43.0	8.0	17.8	25,169.2	8.0	39,369.8	642.7	10.2	21.8	77.2	12.0	31,734.2
Sagem	My 700X	Hungary	3.2	10.4	77.4	5,999.4	10.4	20,073.6	322.3	4.3	35.2	50.2	11.0	42,581.6
Sagem	My 3020	China	<0.001	8.4	57.6	25,027.8	8.4	12,127.8	295.0	3.5	450.8	32.8	7.2	12,362.4
Sagem	My X5-2	Hungary	<0.001	8.8	130.4	34,703.6	8.8	17,318.4	157.8	3.7	22.3	NA	NA	NA
Motorola	C168	Japan	<0.001	8.8	432.4	13,210.8	8.8	28,691.8	13.8	6.3	162.0	NA	NA	NA
Motorola	V220	China	<0.001	10.8	93	10,807.0	10.8	21,270.8	13.5	7.2	1,632.0	NA	NA	NA
Sendo	S360	Korea	<0.001	10.0	61.4	19,756.6	10.0	21,557.8	246.5	5.5	23.2	NA	NA	NA
Mean			**468.4**	**4.9**	**86.1**	**18,367.7**	**10.0**	**27,054.9**	**232.8**	**6.0**	**294.0**	**47.9**	**11.0**	**22,464.4**
SD			**1,116.8**	**1.6**	**95.0**	**9,707.7**	**2.23**	**12,206.1**	**299.6**	**2.5**	**511.3**	**39.1**	**2.4**	**15,834.4**
Min.			**<0.001**	**3.0**	**17.8**	**1,875.8**	**7.40**	**12,127.8**	**4.8**	**3.0**	**14.3**	**20.4**	**7.2**	**5,918.6**
Max.			**2,748.0**	**9.2**	**432.4**	**34,703.6**	**16.0**	**58,742.0**	**1153.5**	**12.8**	**1,820**	**146.8**	**14.4**	**49,772.8**
TTLC			**1,000**	**100**	**2,000**	**1,000**	**100**	**2,000**	**1,000**	**100**	**2,000**	**1,000**	**100**	**2,000**

< 0.001 – below limit of detection by the measuring instrument; NA – not available

In the PWB, the concentration (mean ± standard deviation in parenthesis) of the studied metals ranged from 1,875.8 – 34,703.6 (18,367.8 ± 9,707.7) mg kg^{-1} for Pb, 7.4 – 16.0 (10.0 ± 2.2) mg kg^{-1} for Cd, and 12,127.8 – 58,741.6 (27,054.9 ± 12,206.1) mg kg^{-1} for Ni. The concentration of Pb and Ni in 100% of the samples exceeded their respective TTLC limits of 1,000 and 2,000 mg kg^{-1} [19] by several orders of magnitude, while Cd was within its TTLC concentration limit of 100 mg kg^{-1}. In related reports, high concentrations of Pb exceeding the TTLC limit for Pb in the PWBs of cathode ray tubes [25, 26] and central processing units of computers [27] were observed. Similarly, high Pb concentration in PWBs of mobile phones, ranging from 14,300 – 27,770, 8,222 – 11,600 and 1,000 – 355,000 mg kg^{-1}, respectively, were reported by [20, 28, 29]. The high levels of Pb is attributed to its use in soldering parts of the wiring boards in mobile phones in the form of Sn-Pb solders [30]. It is commonly known that Pb is extremely toxic. It not only causes cancer and affect the hormonal system, but also impacts the nervous system, can hinder development, can cause behavioural problems and impact reproduction [12].

In the BT components, the concentrations (mean ± standard deviation in parenthesis) ranged from 20.4 – 146.8 (48.0 ± 39.1) mg kg^{-1} for Pb, 7.2 – 14.4 (11.0 ± 2.4) mg kg^{-1} for Cd, and 5,918.6 – 49,772.8 (22,464.4 ± 15,834.4) mg kg^{-1} for Ni. The determined concentrations of Pb in mobile phone batteries were all within the TTLC concentration limit of 1,000 mg kg^{-1}. The low level of Pb in the mobile phone batteries can be attributed to the fact that rechargeable batteries used in mobile phones contain little amount of Pb as against the non-rechargeable sealed lead batteries. High Pb levels are thus not expected to be found in smartphones, rather, the batteries of these modern phones contain Li-ion and NiMH. For Ni, the determined concentration in 100% of the studied battery samples exceeded the TTLC limit 2,000 mg kg^{-1}, and the mean concentration exceeded the TTLC limit by about 11 orders of magnitude. In a related study, the concentration of metals in waste portable rechargeable batteries were < 0.001 – 7.9 mg kg^{-1} for Cd and 3,589 – 24,594 mg kg^{-1} for Ni [31]. Ni is described as a toxic and carcinogenic metal and as such, mobile phone batteries are not regarded as being environmentally friendly [6]. The low level of Cd in the batteries in this study can be attributed to the fact that Li-ion and NiMH batteries rarely contain Cd; and the better performance offered by Li-ion batteries as against NiCd batteries has led to a subsequent replacement of NiCd batteries with Li-ion batteries [31]. Although Li-ion batteries are reportedly free of most known toxic metals, Li metal has a high degree of activity, and environmental issues such as pollution of groundwater, emission of greenhouse gases and damage to ecosystems, are commonly associated with mining and processing of Li [32]. Li-ion in batteries uses cobalt oxide in most cases, and the latter has a tendency to undergo "thermal runaway", i.e. it can attain a temperature at which it begins to self-heat, which advances into fire and explosion [33]. Additionally, Li-ion batteries contain metals such as Nd and La, which have limited data on their toxicology and ecotoxicology [34]. The use of such new metals in batteries production could be associated with uncertainties in their EOL, and the consequence could be a case of changing from a known problematic metal to another metal with unknown toxicological profile, which may/may not be problematic [35].

The TTLC is a California requirement that classifies a substance as being hazardous if a determined analyte concentration in that substance exceeds the TTLC limit. This implies that the PWBs and BT components of EOL mobile phones are hazardous wastes with respect to Pb and Ni in the former, and Ni in the latter. Additionally, the general toxicity of many components of electronic wastes led to the formulation of various Directives, which were aimed at restricting the content of toxic substances commonly used in electronic devices. In the European Union, there is the Restriction of Hazardous Substances Directive (RoHS Directive, 2002/95/EC), which limits the content of Pb, Hg, and Cr^{6+} in any homogeneous material, parts or sub-assemblies used in the manufacture of electrical and electronic equipment to 0.1% [16]. The maximum permitted concentration of these elements is 1000 mg kg^{-1} each, except for Cd, where it is 100 mg kg^{-1} [36]. Based on the above Directive, all PWBs tested in this study did not meet the requirements with respect to Pb and Ni; while the BT components did not also conform to the requirement of

this Directive with respect to Ni concentration. However, at the same time, the toxic metallic components of these mobile phone parts can be harnessed and extracted using environmentally sound methods, making them useful waste products and potential resource reserves for these metals.

3.3. Comparison of metals concentration across brands of EOL mobile phones

Figure 3 is a comparison of the average distribution of metals in the dismantled EOL mobile phone parts across brands. Nokia phones had the greatest average Pb and Cd concentrations in the PS component, with values ranging between 460.2 mg kg^{-1} and 12.1 mg kg^{-1}, while Motorola had the greatest Ni content. In the PWB, the Pb concentration in all phone brands ranged from 14,649.4 – 25,169.2 mg kg^{-1}, with Samsung having the greatest concentration, while Sony Ericsson had the least concentration. The mean concentration of Ni in the BT component followed the order by brand: Sony Ericsson > Sagem > Nokia > Samsung, with concentrations ranging from 14,877 – 33,269.4 mg kg^{-1}.

3.4. Matrix spike (recovery studies)

Results for recovery study in validating the chosen analytical procedure is shown in Table 4. Recovery study was conducted on one sample each from the disassembled phone parts, i.e. the phone screens, printed wiring boards, plastic casings and battery components. The percentage recovery for the determined metals fell within the recommended 100 ± 10% [37], and the values ranged as follows: 94.9% - 100.9% for Pb, 96.1% - 100.7% for Cd, and 95.4% - 104.2% for Ni.

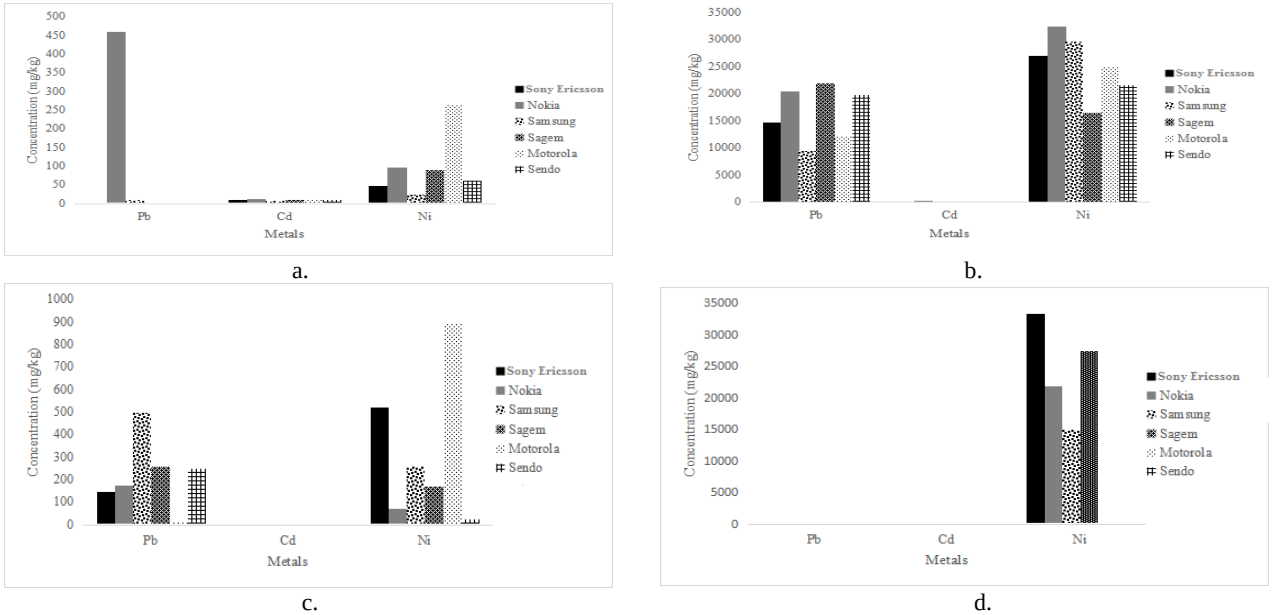


Figure 3. Average metals concentration in different phone brands in: (a) phone screen; (b) printed wiring boards; (c) phone casings; (d) phone batteries

Table 4. Results for matrix spikes and recovery study

Metal	Sample	Concentration of metal in unspiked sample (µg L^{-1})	Expected concentration of metal in spiked sample (µg L^{-1})	Determined concentration of metal in spiked sample (µg L^{-1})	Recovery of metal (%)
Pb	Printed wiring board	125.8	225.8	226.1	100.9
	Phone screen	12.4	112.4	107.4	95.0
	Plastic casing	3.9	103.9	99.2	95.3
	Battery	0.1	100.1	95.0	94.9
Cd	Printed wiring board	0.06	10.1	9.7	96.1
	Phone screen	0.02	10.0	9.9.8	97.7
	Plastic casing	0.08	10.1	10.1	100.7
	Battery	0.07	10.1	9.8	97.3
Ni	Printed wiring board	85.0	185.0	189.3	104.2
	Phone screen	2.2	102.2	99.7	97.6
	Plastic casing	0.3	100.3	95.6	95.4
	Battery	61.8	161.8	165.0	103.2

4. Conclusions

Metals concentration in disassembled components in six different brands of 20 EOL mobile phones were evaluated in this study. Both Pb and Ni exhibited extremely high concentrations in the printed wiring board of all tested samples, with concentrations exceeding their TTLC limits, indicating that this component is hazardous with respect to these two metals. The battery component also displayed exceptionally high concentrations of Ni above TTLC limit. The printed wiring board and battery components of EOL mobile phones are thus hazardous. Therefore, in order to prevent the associated impact these metals

might cause on the environment and human health, measures can be put in place to recover these toxic metals from EOL mobile phone components, thereby rendering these waste products as potential resource reserves for these metals.

Conflict of interest

The authors declare that there are no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgement

The authors are grateful to Messrs Gbenga, Dan and Osakwe of the Chemistry Division, Nigerian Institute of Science Laboratory Technology, Samonda, Ibadan, Nigeria, for their assistance rendered in the course of this work.

References

[1]. N. Gupta, A. Trivedi, S. Hait, Materials composition and associated toxicological impact assessment of mobile phones, Journal of Environmental Chemical Engineering 9 (2021) 104603. Doi: 10.1016/j.jece.2020.104603

[2]. K.G. Maragkos, J.N. Hahladakis, E. Gidarakos, Qualitative and quantitative determination of heavy metals in waste cellular phones, Waste Management 33 (2013) 1882-1889. Doi: 10.1016/j.wasman.2013.05.016

[3]. F. Amiri, M. Moradinazar, J. Moludi, Y. Pasdar, F. Najafi, E. Shakiba, B. Hamzeh, A. Saber, The association between self-reported mobile phone usage with blood pressure and heart rate: evidence from a cross-sectional study, BMC Public Health 22 (2022) 2031. Doi: 10.1186/s12889-022014458-1

[4]. B. Sanou, The world in 2013: ICT facts and figures. Geneva, Switzerland, Retrieved from www.itu.int/ICTFactsFigures2013-e.pdf

[5]. A. Zilberlicht, Z. Wiener-Megnazi, Y. Sheinfeld, B. Grach, S. Lahav-Baratz, M. Dirnfield, Habits of cellphone usage and sperm quality - does it warrant attention? Reproductive BioMedicine Online 31 (2015) 421-426. Doi: 10.1016/j.rbmo.2015.06.006

[6]. O. Osibanjo, I.C. Nnorom, The challenge of electronic waste (E-waste) management in developing countries, Waste Management and Research 25 (2007) 489–501. Doi: 10.1177/0734242X07082028

[7]. R. Muoka, Press release: Telecom sector contributes N2.508 trillion to Nigeria's GDP, Nigeria Communications Commission (2023), retrieved from ncc.gov.ng/accessible/media-centre/news-headlines/1346-press-release-telecom-sector-contributes-n2-508-trillion-to nigeria-s-gdp

[8]. N. Singh, H. Duan, F. Yin, Q. Song, J. Li, Characterizing the materials composition and recovery potential from waste mobile phones: a comparative evaluation of cellular and smart phones, ACS Sustainable Chemical Engineering 6 (2018) 13016-13024. Doi: 10.1021/acssuschemeng.8b02516

[9]. International Precious Metals Institute, IPMI Guidance - Environmentally sound management for used mobile phones. International Precious Metals Institute, IPMI, USA, 2023. Retrieved from https://studylib.net/doc/7314722/ipmi-guidance--environmentally-sound

[10]. Y. Jang, M. Kim, Management of used and end of life mobile phones in Korea: a review, Resource Conservation and Recycling 55 (2010) 11-19. Doi: 10.1016/j.resconrec.2010.07.003

[11]. C.E. Meskers, C. Hagelüken, Closed loop WEEE recycling? Challenges and opportunities for a global recycling society. In: S.M. Howard, (Ed.), EPD-TMS Congress 2009. Proceedings of Sessions and Symposia Sponsored by the Extraction and Processing Division (EPD) of the Minerals, Metals and Materials Society (TMS), San Fransisco, California, USA, pp. 1049–1054.

[12]. S.R. Lim, J.M. Schoenung, Toxicity potentials from waste cellular phones, and a waste management policy integrating consumer, corporate, and government responsibilities, Waste Management 30 (2010) 1653–1660. Doi: 10.1016/j.wasman.2010.04.005

[13]. P. Huang, X. Zhang, X. Deng, Survey and environmental awareness and performance in Ningbo, China: a case study on household electrical and electronic equipment, Journal of Cleaner Production 14 (2006) 1635–1643. Doi: 10.1016/j.jclepro.2006.02.006

[14]. G. Seliger, S.J. Skerlos, B. Basdere, M. Zettl, Design of a modular housing platform to accommodate the remanufacturing of multiple cellular telephone models, 2003 EcoDesign 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan (2003) pp. 243–50. Doi: 10.1109/ECODIM.2003.1322670

[15]. S. Yadav, S. Yadav, P. Kumar, Metal toxicity assessment of mobile phone parts using Milli Q water, Waste Management 34 (2014) 1274-1278. Doi: 10.1016/j.wasman.2014.02.024

[16]. European Commission, Directive 2002/95/EC on the European Parliament and of the Council on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment. Official Journal of the European Union L37 (2003) 19–23.

[17]. US EPA (United States Environmental Protection Agency), Method 3050B: Acid digestion of sediments, sludges, and soils, Revision 2, 1996, Washington, DC. Retrieved from https://www.epa.gov/sites/default/files/2015-06/documents/epa-3050b.pdf

[18]. US CPSC (United States Consumer Product Safety Commission), Test Method: CPSC-CH-E1002-08.3. Standard operating procedure for determining total lead (Pb) in nonmetal children's products, revision, 2009.

https://www.cpsc.gov/s3fs-public/pdfs/blk_media_CPSC-CH-E1002-08_3.pdf

[19]. DTSC (California Department of Toxic Substances), Determination of regulated elements in discarded laptops, LCD monitors plasma TVs, and LCD TVs." Sacramento: California Department of Toxic Substances Control, 2004. http://www.dtsc.ca.gov/hazardouswaste/ewaste/upload/hwmp_rep_sb20_lcd.pdf

[20]. T.A. Majolagbe, Comparison of heavy metals found in waste mobile phones. M.Sc. Thesis, University of Ibadan, 2009.

[21]. B. Rohrig, Chemmatters Article, "smartphones: smart chemistry", American Chemical Society (2015), retrieved from https://www.acs.org/education/resources/highschool/chemmatters/past-issues/archives-2014-2015/smartphones.html, last visited in 21.07.2023.

[22]. O. Tsydenova, M. Bengtsson, Chemical hazards associated with treatment of waste electrical and electronic equipment, Waste Management 31 (2011) 45-58. Doi: 10.1016/j.wasman.2010.08.014

[23]. E. Dimitrakakis, A. Janz, B. Bilitewski, E. Gidarakos, Small WEEE: determining recyclables and hazardous substances in plastics, Journal of Hazardous Materials 29 (2009) 2700-2706. Doi: 10.1016/j.jhazmat.2008.04.054

[24]. I.C. Nnorom, O. Osibanjo, Toxicity characterization of waste mobile phone plastics, Journal of Hazardous Materials 161 (2008) 183-188. Doi: 10.1016/j.jhazmat.2008.03.067

[25]. I.C. Nnorom, O. Osibanjo, K. Okechukwu, O. Nkwachukwu, and R.C. Chukwuma, Evaluation of heavy metal release from the disposal of waste computer monitors at an open dump, International Journal of Environmental Science and Development 1 (2010) 227–233. Doi: 10.7763/IJESD.2010.V1.44

[26]. P.O. Iniaghe, G.U. Adie, O. Osibanjo, Metal levels in computer monitor components discarded within the vicinities of electronic workshops, Toxicological and Environmental Chemistry 95 (2013) 1108-1115. Doi: 10.1080/02772248.2013.863890

[27]. K. Olubanjo, O. Osibanjo, I.C. Nnorom, Evaluation of Pb and Cu contents of selected component parts of waste personal computers, Journal of Applied Science and Environmental Management 19 (2015) 470-477. Doi: 10.4314/jasem.v19i3.17

[28]. J.D. Lincoln, O. A. Ogunseitan, A. A. Shapiro, and J. M. Saphres, Leaching assessment of hazardous material in cellular telephones, Environmental Science and Technology 41 (2007) 2572-2578. Doi: 10.1021/es0610479

[29]. M. Sahan, M.A. Kucuker, B. Demirel, A. Hursthouse, Determination of metal content of waste mobile phones and estimation of their recovery potential in Turkey, International Journal of Environmental Research and Public Health 16 (2019) 887. Doi: 10.3390/ijerph16050887

[30]. N. Wagner, What materials are used to make cell phones? Retrieved from https://www.techwalla.com/articles/what-materials-are-used-to-make-cell-phones, last visited in 30.04.2023.

[31]. I.C. Nnorom, O. Osibanjo, Heavy metal characterization of waste portable rechargeable batteries used in mobile phones, International Journal of Environmental Science and Technology 6 (2009) 641-650. Doi: 10.1007/BF03326105

[32]. C.M. Costa, J.C. Barbosa, R. Goncalves, H. Castro, F.J. Del Campo, S. Lanceros-Mendez, Recycling and environmental issues of lithium-ion batteries: advances, challenges and opportunities, Energy Storage Materials 37 (2021) 433-465. Doi: 10.1016/j.ensm.2021.02.032

[33]. Q. Wang, J. Sun, G. Chu, Lithium ion battery fire and explosion., proceedings of the 8th International Symposium of the Fire Safety Science (2005) 375-382.

[34]. R. Lankey, F. McMichael, Rechargeable battery management and recycling: a green design educational module, Green Design Initiative Technical Report, Carnegie Mellon University (1999) 1-14.

[35]. C.J. Rydh, B. Svard, Impact of global metal flows arising from the use of portable rechargeable batteries, Science of the Total Environment 302 (2003) 167-184. Doi: 10.1016/s0048-9697(02)00293-0

[36]. P. Cusack, T. Perrett, The EU RoHS Directive and its implications for the plastics industry, Plastic Additives and Compounding 8 (2006) 46–49. Doi: 10.1016/S1464-391X(06)70584-0

[37]. L.Q. Ma, G.N. Rao, Chemical fractionation of cadmium, copper, nickel and zinc in contaminated soils, Journal of Environmental Quality 26 (1997) 259-264. Doi: 10.2134/jeq1997.00472425002

Received: 28.03.2023
Received in revised form: 29.07.2023
Accepted: 31.07.2023