

## Assessing the progression of metal concentrations in plastic components and printed wiring boards of end-of-life mobile cell phones

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**Abstract.** This study assessed the progression of Pb, Cd and Cr concentrations in plastic components (PCs) and printed wiring boards (PWBs) of 59 end-of-life (EoL) mobile phones (MPs) produced between 2000 and 2015 by two leading original equipment manufacturers (OEMs) patronized by Nigerians. This was done to study the behavior of OEMs in complying with some widely acceptable regulations. Metals in PCs and PWBs of MPs were extracted following EPA 3050B method and extracts were analyzed using atomic absorption spectrophotometry technique. Furthermore, Toxicity Characteristic Leaching Procedure (TCLP) test was conducted on selected samples to assess metal leachability in landfill conditions. Summary of results (mg/kg) for PCs and PWBs for MPs produced by OEM 1 and OEM 2 in brackets ranged thus: PCs, Pb: 5.00 –195 (LOD-1750), Cr: LOD-6050 (LOD-2170) and Cd: LOD-1.00 (LOD-5.75) while PWBs, Pb: 129-9750 (5.00-12125), Cr: LOD-5488 (LOD- 4000) and Cd: LOD-1.00 (0.25-1.00). There were no regular trends for all metals for both OEMs. Results suggest that a greater percentage of MPs produced till 2015 contained Pb and Cr higher than RoHS and TTLC limits. Furthermore, 50% of TCLP extracts contain Pb higher than EPA limit of 5 mg/L. Therefore, EoL MPs arising in Nigeria should be handled as hazardous materials.

**Keywords:** mobile phone; toxic metals; plastic component; printed wiring board; progression.

### 1. Introduction

Globally, mobile telephony has grown into a major industry in the last 30 years with an estimated 5 billion users around the world [1]. The consumers' attitude of always being attracted to the aesthetics and newer functionalities in more latest versions of electronic products could be influencing the original equipment manufacturers (OEMs) to always roll out products with shorter life spans so that their annual turnover will be greater. Within the last decade, the life span of a typical mobile phone has been put at 9 to 18 months depending on the OEM and how the phone is being used [2]. The ever-advancing telephony technology resulting in increase in product obsolescence and short life span have created an upsurge in the quantities of end-of-life (EoL) mobile phones being disposed of with concomitant toxic substances like Pb, Cd, Cr, Hg, flame retardants, etc. in the various components of the phones, which when improperly disposed of have deleterious consequences on both human health and the environment.

Many studies have reported approximate quantities of EoL mobile phones generated from different countries and regions of the globe [3-7]. In fact, it has been estimated that in the United States alone, over 300, 000 mobile phones are being disposed of daily [1]. A typical mobile phone weighing up to 100 g has been reported to contain over 40 different known metals in different components and in different concentrations [8]. Konstantinos *et al.* [9] explained in details the different components of a typical mobile phone and the average concentrations of major metals and other substances in these components.

As a result of high proportion of some toxic metal concentrations and other organic pollutants in various components of mobile phones and other electrical and electronic equipment (EEE), it is thought that adverse environmental impact could arise from improper management of these EEE at end of life [9, 10]. Within this context, many countries and regions of the world now have policies and regulations in force to restrict the amounts of selected toxic substances in EEE according to their conveniences and the dictates of the laws. Some of the regulations now in force in some countries and regions of the world include: "The European Union 2002/96/EC Waste Electrical and Electronic Equipment Directive" [11], "WEEE Recast Directive" [12], "European Union 2002/95/EC Restriction on Hazardous Substances (RoHS) Directive" [13], "Management methods for the restriction of the use of hazardous substances in electrical and electronic products" [14], "California Department of Toxic Substance Control Laws, Regulations and Policies" [15].

Most developing countries like Nigeria depend completely on imported new and used EEE products including mobile phones. It is perceived that many OEMs customize different EEE to fit each country's environmental laws instead of having a single bill of materials with potentials of being distributed worldwide. Against this backdrop, it is thought that many new EEE products arriving Nigerian shores are substandard possibly due to either weak or non-existence of regulations and enforcement. This could perhaps be the reason why Nigerians patronize a lot of imported fairly used EEE which have comparable prices with new ones and in many cases even more expensive. There is paucity

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of data in literature on studies within the African region that comprehensively and systematically monitor the progression of toxic metal concentrations in mobile phone components produced for a reasonable period of time. Therefore, the objective of this study was to assess the progression of Pb, Cr and Cd concentrations in EoL mobile phones produced between 2000 and 2015 found in repairers' workshops in Nigeria in order to evaluate the behavior of OEMs in regulating the content of the aforementioned metals in their products.

## 2. Experimental

### 2.1 Sample collection

A total of 59 EoL mobile phones produced by two leading original equipment manufacturers coded as OEM 1 and OEM 2 were obtained whole from repairers' shops in Nigeria. Thirty of the phones were produced by OEM 1 while twenty-nine others were produced by OEM 2 all between year 2000 and 2015. The model, date of manufacture (DoM) and country of manufacture (CoM) for each phone were identified and presented in Table 1.

**Table 1.** Details of mobile phones studied.

Original Equipment Manufacturer 1				Original Equipment Manufacturer 2			
YoM	Sample No	IMEI number	CoM	YoM	Sample No	Serial number	CoM
2000	1	351342/80/151028/1	Finland	2001	1	R1XRC74116V	Korea
2000	2	350606/80/908103/7	Finland	2003	2	R4YX551718L	Korea
2001	3	352738/01/129370/1	Finland	2003	3	R5YX307236N	Korea
2002	4	858786/00/643903/5	Hungary	2003	4	R3VX967515D	Korea
2003	5	356672/00/428065/3	Hungary	2004	5	R7VX84672D3	Korea
2003	6	352726/01/089122/8	Hungary	2004	6	RDYND29291D	Korea
2005	7	358376/00/542072/6	Hungary	2005	7	R4WA46504W	Korea
2005	8	358353/00/255050/8	China	2005	8	R2XTC71241A	Korea
2006	9	354841/02/488548/4	Finland	2006	9	RVUP408605L	China
2006	10	354759/00/168768/3	Hungary	2006	10	R6YAA66342B	Korea
2006	11	355516/01/251574/4	Hungary	2006	11	R2UA679986H	Korea
2007	12	356262/01/760739/7	Finland	2007	12	RPTQ828604L	China
2007	13	358250/03/112575/9	India	2007	13	R3UP628331K	Korea
2007	14	353261/01/953380/2	Finland	2008	14	RVMS223B2D	China
2008	15	358291/03/870576/7	India	2008	15	R6XY2442678	Korea
2008	16	A00000015B476E	China	2008	16	RVQQB13551R	Ireland
2008	17	356350/03/020984/4	Finland	2009	17	RVBZA33711M	China
2009	18	353398/04/127620/6	India	2009	18	R3WQA842RF	Korea
2009	19	352708/04/277956/8	India	2010	19	RPZZ13245AD	Philippines
2010	20	352426/05/005202/7	China	2010	20	RD6B482768H	India
2010	21	357420/04/488756/9	India	2010	21	RP5ZC82864B	China
2010	22	357921/04/405718/6	Romania	2011	22	RVHZ708688E	Korea
2011	23	359755/04/535037/4	India	2011	23	RF3BB96984L	China
2011	24	354474/05/148366/6	China	2012	24	R21C601Y1PF	China
2011	25	359764/04/209464/7	India	2012	25	R21D949P8SF	China
2012	26	354131/05/132344/7	India	2012	26	R21C62GFZ6R	China
2012	27	355758/34/278531/6	Finland	2013	27	R21D42SBB8B	China
2013	28	359568/03/762497/3	India	2013	28	RF1DA254DD	Vietnam
2013	29	358912/02/955634/1	China	2014	29	RF1D47RS3XT	Korea
2015	30	354759/00/168709/7	India				

Total recoverable metals were extracted from each sample by adopting the US EPA 3050B Method designed to determine the amount of metals in a material that could become available under the worst-case environmental condition [16, 17]. Exactly 2 g of each

sample were digested using 10 mL of 1:1 HNO<sub>3</sub> for about 15 minutes and allowed to cool. 5 mL of concentrated HNO<sub>3</sub> were added and the solution was heated for about 30 minutes and allowed again to cool. More aliquots of the concentrated HNO<sub>3</sub> (5 mL at a time,

amounting to 10 mL max per sample) were added and the heating process was repeated until no more brown fumes were evolved on heating. This indicated that there was completion of the digestion process. Thereafter, the sample solution was heated up to 90 °C without boiling for about an hour. The solution was then allowed to cool and 2 mL of deionized water and 3 mL of 30% H<sub>2</sub>O<sub>2</sub> were added and the heating process resumed, but gradually to avoid sample loss by effervescence until there was no obvious change in the appearance of the sample solution. Finally, 10 mL of concentrated HCl were added to the solution and again heated at about 95 °C for 15 minutes. The sample solution was allowed to cool; it was filtered through Whatman 41 filter paper into a 50 mL volumetric flask and made up to mark with deionized water. This process was repeated for each sample and the blank. All the extracts were stored in the refrigerator at about 4 °C until analysis.

Because the pH values of the selected samples for toxicity characteristic leaching procedure (TCLP) test were all < 5, TCLP solution 1 and the samples were extracted by adopting the EPA 1311 method [18]. All extracts were analyzed for Pb, Cd and Cr using Buck 205 flame atomic absorption spectrometer (England). The linear ranges for each metal were: 10 mg/L for Pb ( $\lambda$  – 217.0 nm), 2.00 mg/L ( $\lambda$  – 228.9 nm) and 5.00 mg/L for Cr ( $\lambda$  – 357.9 nm). The  $r^2$  values indicating the linearity of the curve for the standards for all the metals ranged from 0.90 – 0.95. Air-acetylene flame which has a less oxidizing nature was used. Analytical grade reagents were used throughout and all glassware used were soaked overnight in dilute HNO<sub>3</sub> acid solution to remove any adsorbed metal on them.

### 3. Results and discussion

#### 3.1. Summary of metal concentrations in mobile phones components

The summary of metal concentrations in both plastic components (PCs) and printed wiring boards (PWBs) for mobile phones (MPs) produced between 2000- 2015 by OEM 1 and OEM 2 is presented in Table 2. The

average concentrations of Pb, Cr and Cd in the PCs of all MPs followed the order Cr >> Pb >> Cd for OEM 1 and Pb > Cr >> Cd for OEM 2. It is obvious from the average results that OEM 1 utilized far more Cr in the PCs compared with OEM 2. It is well known that transition metals like Cr, Cd, Cu, etc. are common inorganic pigments that are usually used to impact colors on materials [19]. The chemistry behind the color formation by transition metals is the  $d-d$  transition arising from the transfer of an electron of a transition metal from a lower  $d$ -orbital to a higher energy  $d$ -orbital. Possibly this advantage was explored to impact colors on PCs of mobile phones studied. Therefore, the elevated concentration of Cr in the OEM 1 PCs may not be unconnected with this. The average metal concentrations in the PWBs of both OEM 1 and OEM 2 followed the trend Pb > Cr >> Cd. The major source of Pb in the PWBs has been identified to be from the Sn/Pb solder which is used to join the wiring circuitry on the board [20]. The average Pb and Cr in PWBs in MPs produced by both OEM 1 and OEM 2 were higher than RoHS Directive limit of 1000 ppm, implying that this component must be handled with care as it is regarded as a hazardous material. Cadmium concentration in all components was far lower than the RoHS limit of 100 ppm. This could be a sign that the two OEMs studied have complied with Cd limit in their EEE components. It is worthy of note that total Cr was determined in the MP components in the present study, but RoHS Directive restrict only Cr (VI) species. Therefore, we may not draw a conclusion on Cr toxicity based on total Cr from RoHS perspective, the Cr content in the components provides a good insight on the amount of Cr still used in MP components. This was the same view by Konstantinos *et al.* [9]. The high standard deviations, in many cases far higher than mean indicated for all metals studied is a sign that the OEMs have different templates for designing perhaps different models, colors and above all for different countries, etc. It is recommended that OEMs should begin to unify their designs across board in an ecofriendly manner for environmental sustainability.

**Table 2.** Summary of metal concentrations (mg/kg) in mobile phone components.

	Mobile phones produced between 2000 – 2015 by OEM 1						Mobile phones produced between 2000 – 2015 by OEM 2					
	Plastic Components			Printed Wiring Boards			Plastic Components			Printed Wiring Boards		
	Pb	Cr	Cd	Pb	Cr	Cd	Pb	Cr	Cd	Pb	Cr	Cd
Mean	39.5	799	0.04	2626	794	0.07	219	149	0.57	2388	1209	0.48
Standard deviation	±53.0	±1720	±0.19	±3056	±1368	±0.21	±399	±408	±1.07	±2740	±1326	±0.19
Median	13.8	7.38	LOD	1000	119	LOD	20	1.50	0.25	1250	838	0.50
Range	5.00-195	LOD-6050	LOD-1.00	129-9750	LOD-5488	LOD-1.00	LOD-1750	LOD-2170	LOD-5.75	5.00-12125	LOD-4000	0.25-1.00
RoHS limit				Pb – 1000 ppm			Cr – 1000 ppm			Cd – 100 ppm		
TTLc limit				Pb – 1000 ppm			Cr - 2500 ppm			Cd - 100 ppm		

$n = 30$  for mobile phones produced by OEM 1;  $n = 29$  for mobile phones produced by OEM; LOD = Limit of detection (mg/L) – Pb = 0.04; Cd = 0.01; Cr = 0.04.

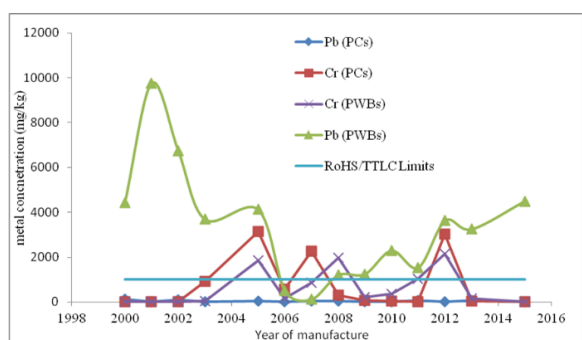
#### 3.2. Progression in the metal concentrations in phone components

Figures 1 – 3 present the progression in metal concentrations in MP components with year of manufacture. These presentations could assist in forecasting OEMs behavior in complying with Directives like EU and China RoHS Directives presently

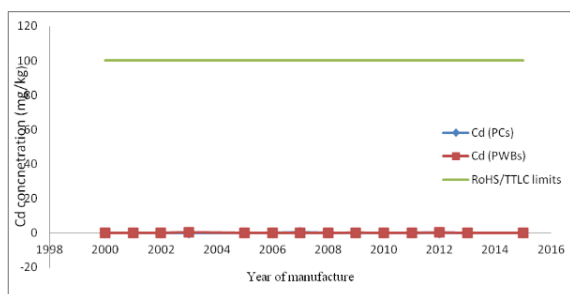
in force in European Union and China, respectively. The concentrations of Pb, Cr and Cd in PCs of MPs produced in 2006 and 2007 by both OEM 1 and OEM 2 when EU and China RoHS Directives, respectively came into force [13, 14] were lower than limit of 1000 ppm for Pb and Cr and 100 ppm for Cd, respectively, except for average Cr concentration in PCs produced by OEM 1 in

2007 and 2012 which showed elevated concentrations higher than 1000 ppm limit (Fig. 1a&b and 2a&b). This trend is perceived to be due to the disparity in color, model and country of manufacture of the products. The concentrations of both Pb and Cr in PWBs of MPs produced between 2000 -2015 did not show any regular trends for both OEM 1 and OEM 2 (Figs 1a and 2a), but a critical look at Pb and Cr contents in MPs produced by OEM 1 (Fig. 1a) indicate a decrease in the metal levels in the later products especially in 2006 and 2007, the years when the EU RoHS and China RoHS, respectively came into force. The enforcement could have influenced the decrease. The same observation was made by Chen *et al.* [21]. Figure 3a indicates a comparison of average concentrations of Pb in MPs produced by OEM 1 and OEM 2. There seem to be no pronounced difference between Pb content in MPs produced by the two OEMs especially from 2006 when RoHS directive came into force. The Pb level fluctuated around the limit for both OEM 1 and 2 till 2011 when there was a steady rise far above the limit in the MPs components produced by both OEMs. This trend is not well understood, but it could be a sign that both OEMs could be producing different qualities of EEE depending on the country of manufacture and the dictates of the extant laws.

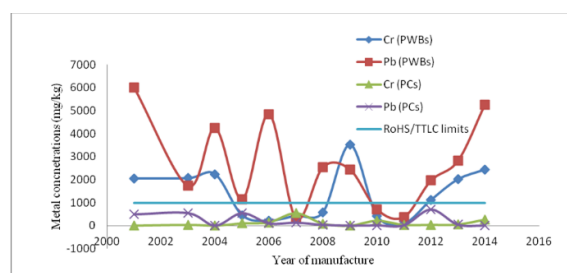
Figure 3b presents a comparison of average Cr concentration in PCs and PWBs of the studied MPs. Chromium level also fluctuated in both components around the limit, but it was very obvious that the level in PCs produced by OEM 2 was lower than in OEM 1, suggesting as earlier indicated a higher patronage of the metal by OEM 1. Figure 3c indicates Cd concentration in the components. In a whole, Cd level was far below the limit of 100 ppm, but there seemed to be higher content in PCs arising from OEM 2 compared to OEM 1, again suggesting difference in patronage by the two OEMs.



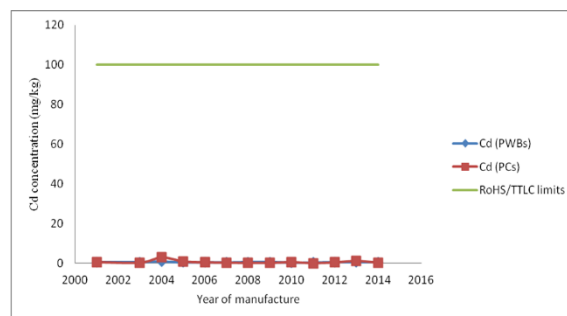
**Figure 1a.** Progression of Pb and Cr concentrations in mobile phones with year of manufacture for OEM 1.



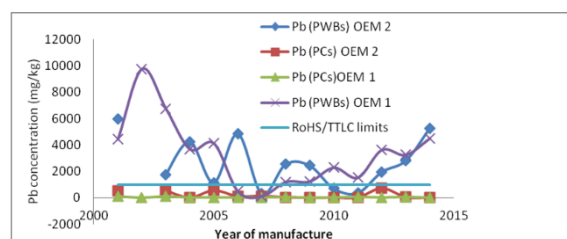
**Figure 1b.** Progression of Cd concentration in mobile phones with year of manufacture for OEM 1.



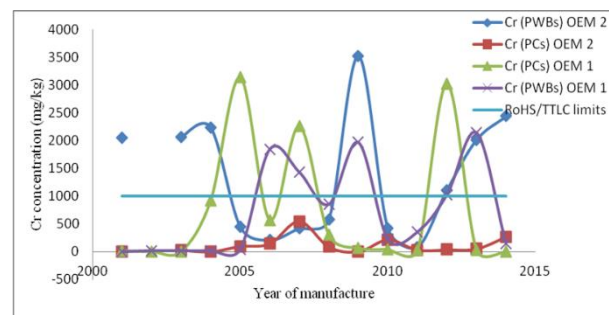
**Figure 2a.** Progression of Pb and Cr concentrations in mobile phones with year of manufacture for OEM 2.



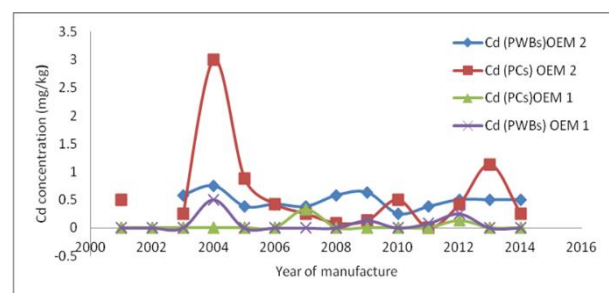
**Figure 2b.** Progression of Cd concentration in mobile phones with year of manufacture for OEM 2.



**Figure 3a.** Comparison of Pb concentration in mobile phones between OEM 1 and OEM 2.



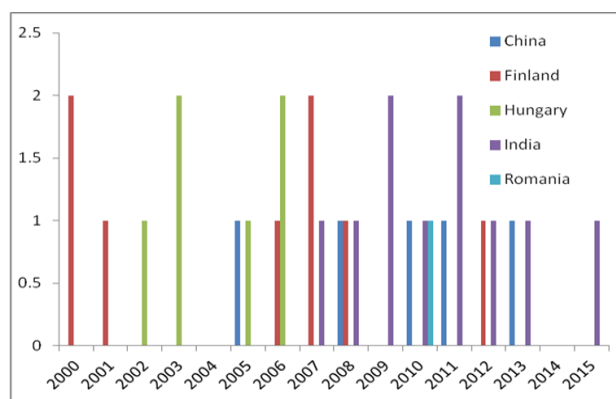
**Figure 3b.** Comparison of Cr concentration in mobile phones between OEM 1 and OEM 2



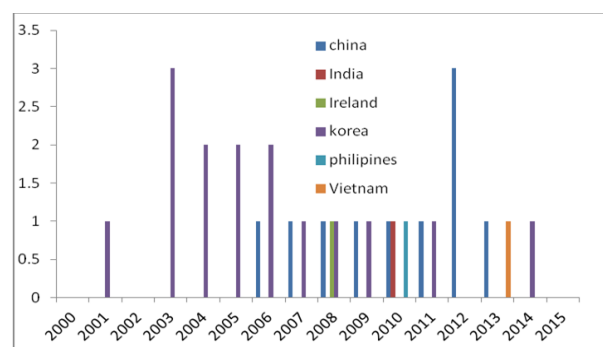
**Figure 3c.** Comparison of Cd concentration in mobile phones between OEM 1 and OEM 2

### 3.3. Distribution of mobile phones studied according to country of manufacture

Figures 4a and 4b show the distribution of MPs according to the country of manufacture. This distribution could provide some insight into linking the levels of the metals in components presented in Figs. 1 - 3 with OEMs' behavior in various countries. The 30 MPs produced by OEM 1 were found to be manufactured in 5 countries as shown in Table 1 and Fig. 4a. Finland, Hungary and Romania are EU countries; therefore, products from these countries should be regulated by EU RoHS Directive which came into force in 2006 and those from China by China RoHS Directive which came into force in 2007. Only India's RoHS is not yet in force. Also, the 29 MPs produced by OEM 2 were found to be from 6 countries, namely: China, India, Ireland, Korea, Philippines and Vietnam. Metals in products from Ireland should have been restricted by EU RoHS Directive and those from China by China RoHS as well. The other Asian countries do not seem to have specific EEE restriction policies or directives in force. An analysis of the results presented in Fig. 1a for instance, indicated that Pb and Cr contents in both PCs and PWBs produced in 2006 by OEM 1 were all lower than 1000 ppm limit for the metals. These concentrations may have been influenced by EU RoHS Directive as the MPs for this year as presented in Fig. 4a were manufactured in Finland and Hungary and two out of the three MPs analyzed were of the same model (Table 1), thereby reducing disparity contributed by design. The drop-in metal content of products manufactured after 2006 compares with the study by Konstantinos *et al.* [9] who investigated the concentrations of selected metals in both PCs and PWBs of 24 obsolete MPs manufactured between 2002 and 2011 found in Greece, an EU country regulated by EU RoHS Directive. Interestingly, the authors found that on the one hand, Pb content in PWBs showed a sharp drop in MPs manufactured between 2007 – 2011 (230 – 510 mg/kg) compared with those manufactured between 2002 - 2006 (100 – 27000 mg/kg) and on the other hand Cr concentration in MPs manufactured between 2002 - 2006 (540 – 8500 mg/kg) and 2007 – 2011 (1500 – 4400 mg/kg) showed lower concentrations in the more recent MPs, but Cr content was still above RoHS limit. This was a sign that the OEMs were shifting towards designing more eco-friendly products.



**Figure 4a.** Distribution of mobile phones produced by OEM 1 according to country of manufacture.



**Figure 4b.** Distribution of mobile phones produced by OEM 2 according to country of manufacture.

In the present study, the metal concentrations of especially Pb in PWBs appeared to be on a steady rise in MPs produced from 2008. This seemed to be the trend for MPs manufactured by OEM 2 also. This trend could probably be influenced by MPs from countries like India for OEM 1 and Asian countries for OEM 2 where EEE specific restriction regulations are not yet in force. Furthermore, it could be a sign that the OEMs customize the concentrations of these restricted materials in different EEE to fit each country's environmental laws instead of having a single bill of materials with potential of being distributed worldwide. It is thought that some OEMs exploit this loophole to produce low quality products meant for export to especially developing countries (as already perceived in Nigeria) where there are either weak or no EEE specific policies/regulations. To buttress this perception, the EU and China RoHS Directives already in force, restrict certain potentially toxic materials in EEE products that are placed only in their countries [13, 14]. One constraint noticed in this study was the inability to identify whether the EoL MPs studied were imported new or used since Nigerians patronize both new and used MPs imported into the country. The implication of these results points to the fact that the two OEMs whose products were studied have not completely complied with the generally accepted RoHS Directive as MPs from countries where RoHS Directive is already in force still contain Pb and Cr in some EoL MP components higher than required, thereby qualifying them as toxic materials. Some studies in literature revealed average Pb concentration in PWBs ranging from 12300 – 201000 mg/kg [22-25]. This range is higher than RoHS Directive limit by many folds, though the studies did not indicate the year and country of manufacture of the MPs investigated to correctly compare with RoHS Directive.

### 3.4. Correlation and ANOVA tests

Table 3 presents Pearson correlations and one-way analysis of variance (ANOVA) both at 95% significant level between Pb, Cr and Cd to study the association of their sources of origin and to compare the averages (means) of the metals, respectively in MPs manufactured by OEM 1 and 2 to know if there is any significant difference between the metal concentrations in them. On the one hand, the  $p$  values for all pairs except Pb/Cr ( $p = 0.0001$ ) for OEM 2 (Table 2) were  $p > 0.05$ , implying no significant differences between the pairs thereby indicating that was close association of



their sources. On the other hand, the *F* values arising from the comparison of average metal concentrations in components of mobile phones manufactured by OEM 1 and OEM 2 indicate that there were no significant differences in the concentrations of Pb and Cr in MP components manufactured by OEM 1 and OEM 2 as the *F* values for the metals were  $> 0.05$ , but there was for Cd (Table 2).

**Table 3.** Correlation and ANOVA tests.

		Pb	Cr	Cd
Pearson correlation	Pb	1	<sup>a</sup> -0.258 ( <i>p</i> = 0.184) <sup>β</sup> [0.688 ( <i>p</i> = 0.0001)]	0.079 ( <i>p</i> = 0.670) [0.029 ( <i>p</i> = 0.889)]
	Cr		1	0.203 ( <i>p</i> = 0.30) [-0.005 ( <i>p</i> = 0.981)]
	Cd			1
One-way ANOVA <i>F</i> values		0.644	0.992	0.000028

Significant if *F* or *p* < 0.05; <sup>a</sup>*p* value for OEM 1; <sup>β</sup>*p* value for OEM 2.

### 3.5. Leaching studies

Table 4 presents the summary of TCLP test on PWBs of mobile phones manufactured by OEM 1 and OEM 2. The results for PCs were omitted because all metals in the PCs for all phones were below detection limits of 0.05 mg/L, 0.02 mg/L and 0.002 mg/L for Pb, Cr and Cd, respectively. 50% PWBs arising from MPs made by both OEM 1 and OEM 2 were higher than EPA limit of 5 mg/L. The TCLP results were within the same ranges with a study by Lincoln *et al.* [22] who examined mobile phone components with ranges (mg/L) of 34.2 - 147 for Pb, 0.04 - 0.13 for Cr and 0.0006 - 0.006 for Cd, respectively. It is thought that Cr and Cd were detected in this study because Inductively Plasma - Mass Spectrometer, a more sensitive with lower detection limits for the metals was used.

**Table 4.** Summary of leaching studies on mobile phone components.

OEM 1 (PWBs)		OEM 2 (PWBs)	TCLP limit mg/L	
Total recoverable (mg/kg)	TCLP (mg/L)	Total recoverable (mg/kg)	TCLP (mg/L)	
Pb	Pb	Pb	Pb	
9750	92.8	6000	109	5
7750	38.8	925	144	5
250	0.11	3000	0.29	5
2125	39.4	3925	288	5
3375	0.51	4875	10.8	5
250	0.42	125	0.57	5
7000	35.9	1500	0.27	5
5500	50.7	4375	10.3	5

Detection limit: Pb - 0.05 mg/L

## 4. Conclusion

This study presents an evaluation of Pb, Cr and Cd contents in plastic components and printed wiring boards of 59 mobile phones made between year 2000 - 2015 in 11 different countries across Asia and Europe by two leading original equipment manufacturers. The results revealed that despite the restrictions of the aforementioned metals by one of the most widely and globally accepted directive, the RoHS Directive, Pb and Cr were still found especially in printed wiring boards

higher than RoHS limits even in mobile phones manufactured in countries where RoHS Directive was already in force. This is a wake-up call to encourage the OEMs to adopt the principle of manufacture-for-environment by shifting towards designing more eco-friendly products to safeguard human health and the entire environment. Furthermore, EOMs should implement the policy of a single bill of materials with the intention of being distributed worldwide, instead of perhaps customizing less quality materials based on the extant regulations for countries with weaker or no enforcement of restriction laws in place.

## Conflict of interest

No conflict of interest declared.

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