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RECYCLABILITY OF WASTE PRINTED CIRCUIT BOARDS AND WASTE PLASTIC HOUSINGS FROM ELECTRONIC WASTE MATERIALS IN GHANA

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Abstract

This study examined the content of risk elements, including those controlled by restriction of hazardous substances (RoHS) and total threshold limit concentration (TTLC) regulatory standards, in waste printed circuit boards (WPCBs) and waste plastic housings (WPHs) of common e-waste materials in Ghana and assessed their recycling potential. Twenty-four WPCBs and 47 WPHs were collected from individuals, e-waste recycling sites, and electrical and electronic repairers' workshops in the Greater Accra Region. Each of these samples was analysed for 30 risk elements at SGS Laboratory, Ghana, using inductively coupled plasma atomic emission spectrometry. Results revealed that all analysed elements were present in nearly all samples, except Se, which was below the detection limit (<0.01 mg/kg) in all WPCBs. Arsenic (As), Se, Sb, and Sn were absent in some WPHs. Levels of Cu in all the WPCBs exceeded the TTLC limit of 2500 mg/kg. Similarly, levels of Pb in some WPCBs were more than the RoHS limit of 1000 mg/kg. However, none of the WPHs had concentrations of risk elements to be more than the regulatory standards. The elevated Cu and Pb levels in the boards make them to be hazardous, thereby necessitating strict handling under hazardous waste management protocols. Overall, the diverse and significant concentrations of valuable risk elements in WPCBs and WPHs could be potential secondary raw materials for electronics industry. Therefore, it is necessary to develop suitable and sustainable technologies for their recovery through effective recycling.

Keyword: Waste printed circuit boards, waste plastic housings, risk elements, recycling potential, Ghana

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Introduction

The electronics industry is the world's most significant, fastest-growing manufacturing sector (Liyakat & Liyakat, 2023). Rising demand for newer and innovative technological products, coupled with their high rate of obsolescence, can account for this remarkable growth. Consequently, large quantities of e-waste from computers, mobile phones, television sets (TVs), etc., are produced globally (Forti et al., 2020). It is estimated that 53.6 million metric tons (Mt) of electrical and electronic waste (e-waste) were generated in the year 2019 alone, with an estimated yearly increment of 2 Mt (Forti et al., 2020). This phenomenon has compelled the need to recycle and reuse obsolete products (or e-waste). For instance, the European Union's Waste Electrical and Electronics Equipment (EU-WEEE) Directive 2012/2019 sets mandatory targets for the collection, recovery, and recycling of end-of-life (EoL) electrical and electronic equipment (EEE) (Penttilä, 2020). This will minimise environmental impact of e-waste and resource depletion associated with the electronic industry (Penttilä, 2020). According to Wäger et al. (2011), recycling plastics, instead of using raw materials, causes a decline in their harmful environmental impact. Moreover, in case of recycling e-waste, it will meet the global demand for metal production, because e-waste materials destined to be disposed of in landfills will be turned into reusable form (Kumar et al., 2017).

Nonetheless, various regulatory standards are in place to ensure that the recycling of e-waste does not have adverse effects on human health and the environment, despite the presence of toxic substances in them (Maphosa & Mashau, 2020). Such standards include the EU's Restriction of Hazardous Substances (RoHs) Directive 2011/65/EU and California's Total Threshold Limit Concentration (TTLC) limits. The EU-RoHS directive regulates certain hazardous substances in EEE; it specifies the maximum limits for concentrations of ten regulated materials, which include three risk elements: lead (Pb), mercury (Hg), and cadmium (Cd) (EU, 2011). The TTLC limits determine whether solid waste can be considered as hazardous, based on specified concentration thresholds, with elements such as copper (Cu), barium (Ba) and molybdenum (Mo) contents (DTSC, 2005a).

E-waste contains both plastics and printed circuit boards (PrCBs). Plastic polymers are used as insulators and/or lightweight parts in EEE. Their composition in WEEE ranges from 2.8 % to 72.3 %, depending on the type of EEE (Lahtela et al., 2022). Elements such as Pb, Cd, chromium (Cr), Hg, bromine (Br) and tin (Sn) are often added to plastic polymers as pigments, fillers, ultraviolet (UV) stabilizers and/or flame retardants. Usually, these materials are added as compounds that often do not chemically bond with molecules of plastics. Rather, they create a suspension in the solid plastic polymer (Nnorom & Osibanjo, 2009). On the other hand, PrCB, which is the most precious component of EEE, accounts for 3 to 6 wt% of the total e-waste (Wang et al., 2020). These materials contain about 60 elements, which are categorised into metals, non-metals and organics (Force, 2009; Szałatkiewicz, 2014). The metal components largely include iron (Fe), silver (Ag), nickel (Ni), antimony (Sb) and bismuth (Bi) (Goosey & Kellner, 2003).

In Ghana, both waste plastic housings (WPHs) and waste printed circuit boards (WPCBs) (sometimes after partial metal recovery, mainly copper) become unessential. They are either stored or scattered in the environment, although these materials are vital sources of Cu and other elements (Maphosa & Mashau, 2023) for recovery and utilisation as raw materials by various industries, including the electronics manufacturing sector. Unfortunately, these waste materials, whether left in the environment or stored, pose a threat to the economy, environment, and human health

(Manikkampatt Palanisamy et al., 2022). It has been projected that a metric ton (1,000 kg) of WPCB alone contains recoverable metals valued at about US$ 92,000 (Suponik, 2025). Thus, failing to recycle them results in direct economic losses. In addition, risk elements such as Pb and Cd, among others, in these waste materials can be released into the environment, where they are easily converted and transmitted to be parts of foodstuffs and drinks (Bortey-Sam et al., 2015; Lente et al., 2022; Osei-Owusu et al., 2023; Donkor et al., 2017). If these toxic substances are consumed in food and drinks, they cause various human health-related problems in vital organs of babies, children and adults (Zeng et al., 2017; Donzelli et al., 2019; Singh et al., 2021; Abubarkar et al., 2022; Dutta et al., 2022). This study, therefore, aims to: (i) examine levels of some risk elements in common e-waste materials in Ghana and (ii) suggest some potential opportunities for recycling.

Materials and Methods

Sample collection and preparation

A total of twenty-four WPCBs and 47 WPHs of different WEEE (mobile phones, television sets, desktop computer monitors, laptop monitors, printer cartridges, calculators and radio sets) were collected between October and November 2015 from individuals, EEE repairers' workshops and e-waste recycling sites in the Greater Accra Region of Ghana. The samples were placed in Ziploc bags and transported to the University of Ghana Chemistry laboratory. The product brand name, origin, and release date were recorded if available. Each WPCB and WPH sample was covered with a clean white cloth to protect and avoid cross-contamination, then crushed using a hammer. The sample size was further reduced to less than 2 mm using a ceramic-coated cutting mill.

Sample analysis

An amount of 0.5 g of each WPCB and WPH sample was digested in polypropylene containers with 10 ml aqua regia (3HCl: 1 HNO_3) solution. Triplicate samples of both the WPCBs and the WPHs fractions were digested. The solutions were heated continuously for 6 hours at 120 °C to near dryness. The digest was re-solubilized with 10 mL volume of deionized water and then filtered and brought to 50 mL and analysed using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) (PerkinElmer Optima 5300 DV), and levels were obtained in triplicate analysis. In all, a total of thirty risk elements (Cu, Bi, Sn, Ca, Ni, Al, Ti, B, Mg, Na, Zn, Si, Pb, K, Mn, Sr, As, Zr, Be, Co, Cr, Ag, Li, Ba, V, Mo, P, Cd, Sb, and Se) were analysed. The detection limit were as follows: 0.02 mg/kg - Ag, Al, Cr, Sb, Sn; 0.01 mg/kg - As, B, Ba, Be, Bi, Cd, Co, Cu, Hg, Li, Mo, Ni P, Pb, Se, Sr, Ti, V, Y, Zn, Zr; 1.00 mg/kg - Ca, K, Na; 0.1 mg/kg - Si.

Quality Assurance

Quality control/assurance measures were carried out to ensure the reliability of results. All glassware was thoroughly cleaned and soaked in 5% nitric acid (HNO_3) overnight, then rinsed with de-ionized water before use (Ishak et al., 2015). To avoid cross-contamination, sample preparation tools were cleaned after each sample was prepared. Analytical-grade reagents and sample blanks were used. All samples were analysed in triplicates.

Data Analysis

The experimental data obtained were evaluated by descriptive statistics, analysis of variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) statistical tests using the statistical tool package in Microsoft® Excel® for Microsoft 365 MSO (Version 2405 Build 16.0.17628.20006) 64-bit.

Results and Discussion

Risk Elements in Waste Printed Circuit Boards (WPCBs)

Thirty (30) different risk elements (Ag, Al, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Se, Si, Sn, Sr, Ti, V, Zn, and Zr) were analysed in this study. Table 1 shows the average concentrations from WPCBs of television sets (TVs), radio sets, mobile phones, laptops, and desktop computer monitors. Generally, of the thirty elements analysed, only Se was below the 0.01 mg/kg detection limit in all the samples. The results reflect the wide range of elements found in WPCBs (Van et al., 2021; Vidyadhar, 2016; Szałatkiewicz, 2014). However, there were variations in the concentrations of risk elements observed in the different boards due to factors such as their nature (whether electric or electronic), the type of device, year of manufacture (Szałatkiewicz, 2014; Anić-Vučinić et al., 2020) and the extent to which the recovery of essential component was done (for those that various components have been retrieved and are scattered in the environment). In the current study, the TV boards (TVB), laptop monitor boards (LMB), and mobile phone boards (MPB) exhibited relatively pronounced concentrations of risk elements. In contrast, radio boards (RB) showed the lowest levels for most elements (Al, B, Ba, Co, Cr, Li, Mo, Ni, Si, Sn, Sr, Ti, Zn and Zr). This low concentration observed in the RB results from their very nature, which is generally not as complicated as others. It is worth noting that PrCBs serve as the platform upon which components, such as semiconductor chips and capacitors, are mounted, providing electrical connections between these components. Elements such as Al, Cu, and Bi were much higher than those of Cd, Mo, and vanadium (V) (Table 1). The high levels of these elements suggest that these e-waste materials can serve as a source of raw materials for the electronics industry if proper techniques are employed to recover them. Various recovery technologies such as pyrometallurgy, hydrometallurgy, electrometallurgy, and biometallurgy have been discussed in literature (Dutta et al., 2023; Rene et al., 2021; Kaya, 2019Hadi et al., 2015).

Comparing the results with the TTLC limits, at least Cu and Pb can be a considerable concern in terms of human health and the environment. The average concentration of Cu in all the WPCBs exceeded the TTLC limit of 2500 mg/kg (DTSC, 2005a). Similar trend was observed for Pb, except in LMB. Priya & Haiti (2017) also reported concentrations of Cu to be (201300 ±400 mg/kg) in LMB, whereas that of Pb was 22600±800 mg/kg in TVBs. Thus, levels of both Cu and Pb were above the TTLC limits (DTSC, 2005a). Additionally, Cu levels in DCMB (i.e., 6505.6 mg/kg) observed in this study were lower, when compared to those ranging from 142000 to 25014 mg/kg in reports (Yamane et al., 2011; Kolias et al., 2014; Bizzo et al., 2014). Conversely, Nnorom et al. (2010) reported a lower concentration of 877 mg/kg. Furthermore, the concentration of Pb in the WPCBs exceeded the RoHS limit in all cases except for LMB. According to Anić-Vučinić et al. (2020), Cu is one of the significant components of bare boards of WPCBs. Sources of Pb in PrCBs include Pb soldering (Jha et al., 2012).

In fact, levels of Cu in TVB, MPB, DCB and LMB were significantly ($p<0.05$) different. However, levels of Pb in TVB, MPB, DCB and LMB were not significantly ($p>0.05$) different. Thus, a significant variation in Cu concentrations among the four WPCBs, unlike Pb concentrations in similar e-waste materials. Furthermore, a Tukey's HSD post-hoc analysis for Cu showed that MPBs contained significantly higher Cu levels than all other groups, followed by the LMB. The concentration of Cu in the TVB and DCB showed minimal difference.

Table 1: Average risk element concentrations (mg/kg) in printed circuit boards

RE	MPB *n=11*	*Std.*	TVB *n= 7*	*Std.*	DCMB *n=2*	*Std.*	RB *n=1*	LMB *n=3*	*Std.*	TTLC limit	RoHS limit
Ag	122.80	104.46	38.48	24.79	32.20	5.06	29.62	127.97	7.59	500	-
Al	57508.55	27624.43	4530.45	8898.75	46785.50	8573.67	1329.6	1024.12	105.24	-	-
As	101.83	160.27	4.96	7.13	6.83	3.48	2.48	11.28	1.91	50	-
B	16000.48	7995.31	1059.70	2103.16	14024.00	5704.94	178.44	27474.33	2548.76	-	-
Ba	135.10	122.08	38.61	44.34	54.31	49.64	18.77	339.99	361.56	10000	-
Be	32.06	65.2	nd	-	nd	-	0.007	nd	-	75	-
Bi	16907.64	2548.23	5869.00	8264.39	6262.00	2315.07	4352.5	14334.00	2064.91	-	-
Ca	124771.45	55311.24	18764.86	20289.16	1163.25	466.34	11006	240456.67	29129.71	-	-
Cd	0.02	0.06	9.07	18.14	2.60	2.75	4.72	nd	-	100	100
Co	53.97	69.55	12.94	15.83	19.65	23.87	1.47	36.67	40.01	8000	-
Cr	69.42	49.61	109.77	134.24	14.32	8.49	1.581	98.51	10.26	2500	1000
Cu	17479.36	2655.11	2782.71	1297.09	6505.60	2408.41	4598.9	14879.67	1850.46	2500	-
K	2050.36	785.47	1363.39	1199.62	1752.50	259.51	2116.1	1593.33	404.93	-	-
Li	65.85	25.02	7.09	9.31	33.23	11.69	4.51	55.76	19.29	-	-
Mg	5355.73	1275.63	4212.71	807.29	105.37	149.01	3389	6923.00	1373.91	-	-
Mn	236.89	479.28	593.61	1340.45	59.88	13.72	16.77	99.18	32.00	-	-
Mo	13.21	13.65	0.63	1.10	12.00	15.03	nd	1.44	1.25	3500	-
Na	4811.91	1803.00	3147.00	722.00	5083.00	562.86	7867	6857.33	997.57	-	-

RE: Risk element, MPB: Mobile phone board, TVB: Television board, DCMB: Desktop computer monitor board, LMB: Laptop monitor board, RB: Radio board, TTLC: Total Threshold Limit Concentration, RoHS: Restriction of hazardous substances, n: number of samples and nd: not detected, std: standard deviation.

Table 1 (continued): Average risk element concentrations (mg/kg) in printed circuit boards

RE	MPB *n=11*	*Std.*	TVB *n= 7*	*Std.*	DCMB *n=2*	*Std.*	RB *n=1*	LMB *n=3*	*Std.*	TTLC limit	RoHS limit
Ni	41932.82	23563.37	7117.62	10425.01	22.59	16.82	17.56	15390.00	11682.01	2000	-
P	nd	-	3373.43	8147.00	nd	-	nd	nd	-	-	-
Pb	2168.73	726.29	4720.71	4044.04	2406.00	813.17	3189	983.38	144.71	1000	1000
Sb	0.99	3.28	74.36	192.85	193.67	222.71	17.91	0.84	1.45	500	-
Se	nd	-	nd	-	nd	-	nd	nd	-	100	-
Si	3630.91	1309.76	528.41	917.58	4864.50	1028.84	137.01	3782.40	783.69	-	-
Sn	72643.45	52721.04	34224.86	47477.99	10565.50	7397.04	1020.81	15366.00	14159.71	-	-
Sr	883.84	552.64	128.77	148.01	843.73	563.24	71.88	418.19	53.75	-	-
Ti	6567.76	7287.20	665.26	848.22	728.36	101.44	50.04	6384.00	4280.05	-	-
V	48.09	27.77	13.61	25.86	10.56	0.52	1.10	77.81	13.71	2400	-
Zn	1595.61	916.57	343.41	306.85	309.30	204.50	189.81	527.11	301.85	5000	-
Zr	173.06	196.51	4723.00	12495.88	68.56	26.35	2.29	286.21	95.23	-	-

RE: Risk element, MPB: Mobile phone board, TVB: Television board, DCMB: Desktop computer monitor board, LMB: Laptop monitor board, RB: Radio board, TTLC: Total Threshold Limit Concentration, RoHS: Restriction of hazardous substances, n: number of samples and nd: not detected, std: standard deviation.

Risk Elements Concentrations in Plastics Housing (PH)

The average concentrations of risk elements in eight different WPH samples of e-waste are shown in Table 2. All thirty elements analysed were detectable in all the WPHs, except As, Be, B, Se, and Sn. However, unlike the WPCBs, the concentrations of the various elements analysed in the WPHs were relatively lower. A similar trend was observed by Kolias et al. (2014). In general, aluminium (Al), calcium (Ca), Cu, magnesium (Mg), sodium (Na), and phosphorus (P) concentrations were comparatively higher than those of the remaining analysed elements. Ca had the highest mean element concentration (Table 2). This could be due to their use as fillers to enhance the material's properties (Ahmad Fauzi et al., 2022). Al is also used as a coating on plastics to improve their mechanical properties (Irawan, 2018). In effect, concentrations of Ca in this study ranged from 93.91 mg/kg to 21,192.00 mg/kg, whereas those of Al ranged from 6.71 mg/kg to 2249.30 mg/kg (Table 2). Comparing the levels of metals in the various WPHs, the mean values of their concentrations in the TV plastic housing (TVH) were the highest, followed by those in desktop computer housing (DCH). However, calculator housing (CH) had the lowest.

Moreover, the mean concentrations of risk elements for all the WPHs were below the RoHS and TTLC regulatory limits. Similar trends were observed by Stenvall et al. (2013) and Singh et al. (2020), corroborating findings in this study.

Implications for recycling

WPCBs and WPHs contain high levels of valuable elements. Hence, these elements make e-waste to be re-utilisable (Cayumil et al., 2014; Sahajwalla & Gaikwad, 2018). The valuable risk elements observed in this study support this fact. However, the recovery rate often depends on the extraction method (Dutta et al., 2018; Sahajwalla & Gaikwad, 2018). The traditional processing of metal extraction across Ghana, involves manual dismantling by opening burning of WPCBs to recover Cu. In fact, these recovery methods are insufficient in retrieving all functional components. Many risk elements left behind after the traditional recovery approaches are employed, thereby requiring effective recycling to be done. This is because environmental problems are apparently associated with the traditional recovery method, which leave traceable risk elements e-waste debris behind in the environment. Hence, the elements in these materials can be leached out into soil to cause pollution (Donkor et al., 2017; Sepúlveda et al., 2010). According to Mao et al. (2020), the migration rate of risk elements such as Cu and Pb in plastics accelerates over time. Therefore, there is a need to develop suitable and sustainable technologies for their recovery through effective recycling.

However, when recovering these essential elements, it is necessary to determine whether the recovery approaches comply with regulatory measures such as the TTLC and RoHS limits. This is because the WPCBs and the WPHs in this study had concentrations of Cu being above the TTLC, whereas concentrations of Pb in all the WPCBs exceeded the RoHS limit, except in the LMB. Regarding these regulatory limits, once a particular substance fails, the entire material is considered hazardous (Okenwa-Ani et al., 2019), which disqualifies it from unrestricted recycling, thereby meriting mandatory hazardous waste handling protocols. Each country's laws and regulations typically establish these protocols. Ghana's compulsory hazardous waste management protocols are detailed in the Hazardous and Electronic Waste Control and Management Act, 2016 (Act 917), along with its associated regulations. These protocols specify that hazardous waste must only be handled by authorised collectors, treatment, storage, and disposal facilities (EPA, 2018).

The types of risk elements and their concentrations directly affect the suitable technology for their recovery. For instance, the level of Pb complicates both mechanical and thermal recycling (Li et al., 2024; Zhou & Qiu, 2010). According to Zhou & Qiu (2010), mechanical processes such as crushing and separation can result in the release of Pb into the environment. Additionally, high levels of Pb increase the risk of Pb vapour emissions during smelting, requiring strict emission controls and strong worker protection measures (Li et al., 2024; Song & Li, 2014).

The current study revealed that MPBs contain significantly more Cu than that in all the other "boards". They represent the most valuable source for Cu recovery. Hence, they should be prioritised in recycling efforts or targeted with more efficient recovery technologies. The LMB can be regarded as a secondary priority for Cu recovery. For Pb, the lack of significant differences indicates that all WPCB types offer similar lead recovery potential, so no specific board type has a clear economic advantage for Pb recovery. Consequently, Pb recovery can be approached uniformly across all board types without the need for separation based on Pb content.

Table 2: Average concentrations of risk elements (mg/kg) in e-waste plastic housings

RE	TVH n=15	Std.	RH n=5	Std	DCH n=8	Std.	MPH n=11	Std.	TTLC limit	RoHS limit
Ag	5.23	11.38	0.25	0.22	0.51	0.38	13.84	35.57	500	-
Al	1233.25	1325.37	720.65	488.93	407.74	261.35	2116.07	1797.09	-	-
As	9.16	17.85	1.12	2.02	3.59	7.09	2.81	3.55	50	-
B	114.33	106.59	43.43	8.33	47.44	34.33	24.30	6.49	-	-
Ba	85.78	68.45	183.41	73.40	119.42	143.44	150.98	283.15	10000	-
Be	0.03	0.06	0.16	0.09	0.19	0.19	0.04	0.10	75	-
Bi	1197.70	1590.15	53.95	22.52	81.57	125.12	69.36	33.55	-	-
Ca	17871.60	11280.25	21192.00	5214.39	4401.81	2478.50	3655.00	1825.30	-	-
Cd	0.98	0.70	0.88	1.71	4.10	11.23	1.50	3.50	100	100
Co	1.96	4.07	0.65	0.52	51.65	143.00	1.12	1.14	8000	-
Cr	301.28	397.13	271.02	112.75	255.93	150.16	122.78	28.63	2500	1000
Cu	722.17	1089.53	54.41	23.81	41.73	27.50	169.89	268.51	2500	-
K	758.40	177.73	624.85	198.25	658.68	196.74	730.14	280.37	-	-
Li	11.83	7.04	10.20	4.02	5.81	9.08	3.86	4.32	-	-
Mg	7736.06	11949.79	6101.04	1323.89	2154.31	2352.41	621.63	418.08	-	-
Mn	243.12	202.87	84.18	39.16	42.40	14.63	22.45	4.94	-	-
Mo	63.57	31.84	55.25	22.94	17.49	9.71	6.05	3.32	3500	-
Na	3142.60	1114.60	3319.98	709.27	921.44	364.13	916.02	446.82	-	-
Ni	87.83	80.67	87.20	6.52	81.83	32.36	225.27	436.20	2000	-
P	1318.83	4930.80	543.61	1006.60	540.08	370.37	384.92	456.44	-	-
Pb	217.91	655.05	32.68	35.29	17.17	6.81	30.77	20.07	1000	1000
Sb	124.58	385.09	4.30	3.14	397.05	108.25	16.26	33.36	500	-
Se	94.62	135.03	nd	-	57.09	73.22	0.79	1.92	100	-
Si	361.06	479.56	73.20	17.77	136.35	155.91	47.70	18.87	-	-
Sn	80.83	115.34	9.32	18.63	2.97	7.14	3.12	6.17	-	-
Sr	109.09	45.89	128.52	21.11	41.21	63.00	6.61	6.12	-	-
Ti	1178.74	3475.26	196.66	166.71	151.53	108.87	521.89	832.14	-	-
V	4.80	3.68	1.84	0.65	3.01	3.96	1.77	0.71	2400	-
Zn	1301.47	990.67	565.07	255.40	161.22	85.29	179.78	182.93	5000	-
Zr	4.25	4.22	1.87	0.76	3.86	3.99	82.85	65.01	-	-

TVH-television housing, RH-radio housing, DCH- Desktop computer housing, MPH-mobile phone housing, PrCH-printer cartridge housing, CH-calculator housing, LBH-laptop battery housing, TTLC: Total Threshold Limit Concentration, RoHS: Restriction of hazardous substances, n: number of samples and nd: not detected, std: standard deviation.

Table 2 (continued): Average concentrations of risk elements (mg/kg) in e-waste plastic housings

RE	PrCH n=5	Std.	LBH n=1	CH n=1	FH n=1	TTLC limit	RoHS limit
Ag	0.04	0.63	2.21	0.47	0.47	500	-
Al	6.72	2.82	294.60	0.41	1327.13	-	-
As	0.34	0.42	nd	nd	nd	50	-
B	0.37	0.08	14.48	nd	105.71	-	-
Ba	2.63	3.96	12.31	37.45	1234.24	10000	-
Be	nd	-	0.25	1884.31	0.2	75	-
Bi	0.71	0.51	134.53	0.40	132.58	-	-
Ca	186.98	232.21	3960.81	93.91	11207.02	-	-
Cd	0.28	0.35	12.40	12.36	2.19	100	100
Co	0.05	0.08	0.93	0.821	27.13	8000	-
Cr	1.32	0.32	96.92	0.53	139.81	2500	1000
Cu	0.66	0.48	124.01	221.44	124.06	2500	-
K	4.43	0.89	577.21	5686.80	417.82	-	-
Li	0.04	0.04	1.42	664.31	3.71	-	-
Mg	23.72	15.45	396.00	10.81	1085.53	-	-
Mn	0.36	0.20	13.61	5102.05	105.12	-	-
Mo	0.02	0.01	6.35	65.06	9.21	3500	-
Na	9.62	3.16	737.20	52.52	859.27	-	-
Ni	0.57	0.32	74.21	2947.1	110.12	2000	-
P	7.35	9.73	293.91	82.63	7702.14	-	-
Pb	0.14	0.19	11.20	440.08	128.84	1000	1000
Sb	10.65	6.26	nd	14.13	59.81	500	-
Se	0.11	0.13	nd	10.59	nd	100	-
Si	2.23	0.82	16.40	nd	118.73	-	-
Sn	nd	-	nd	129.81	nd	-	-
Sr	0.54	0.35	4.11	nd	24.84	-	-
Ti	0.11	0.06	54.08	147.24	8.21	-	-
V	0.01	0.00	1.13	87.37	1.70	2400	-
Zn	5253.59	10463.71	82.90	2.23	896.91	5000	-
Zr	0.01	0.00	0.82	359.31	0.21	-	-

TVH: Television housing, RH-radio housing, DCH- Desktop computer housing, MPH-mobile phone housing, PrCH-printer cartridge housing, CH-calculator housing, LBH – laptop battery housing, TTLC: Total Threshold Limit Concentration, RoHS: Restriction of hazardous substances, n: number of samples and nd: not detected, std: standard deviation.

Conclusion

Generally, WPCBs had higher concentrations of risk elements than WPH had. Levels of Cu in all the studied WPCBs exceeded 2500 mg/kg, which is the TTLC limit. Similar trends were observed for Pb regarding TTLC and RoHS limits (1000 mg/kg), except in the LMB. Regarding the RoHS and TTLC regulatory limits, all the WPCBs were considered hazardous and should therefore be managed under strict hazardous waste protocols. Among the WPCBs, MPBs contain a considerable amount of Cu, which should be the primary focus for recovery. Further research is necessary to determine the levels of risk elements in other components of e-waste, as well as in other types of WEEE not covered in this study. Additionally, it is crucial to investigate the presence of other toxic substances, such as BFRs, phthalates, and other organic toxicants, in WPHs and WPCBs, especially those classified as POPS under the Stockholm Convention. Moreover, further studies are needed to assess the economic viability of metal recovery from WPCBs and WPH using various extraction techniques, such as hydrometallurgical, pyrometallurgical, or bioleaching methods, along with life-cycle assessments.

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