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ASSESSMENT OF THE RECYCLING POTENTIAL OF WASTE PRINTED CIRCUIT BOARDS (WPCBS) AND WASTE PLASTIC HOUSINGS (WPHS) OF ELECTRONIC WASTE MATERIALS IN GHANA'S ENVIRONMENT

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Abstract

The study aimed to examine the content of some risk elements, including those imposed by Restriction of Hazardous Substances (RoHS) and Total Threshold Limit Concentration (TTLC) regulations, in waste printed circuit boards (WPCBs) and waste plastic housings (WPHs) of some common e-waste materials in the Ghanaian environment and determine their potential for recycling. Forty-seven WPCBs and twenty-four WPHs of different electrical and electronic equipment were collected from individuals, e-waste recycling sites, and electrical and electronic workshops in the Greater Accra Region of Ghana. The samples were analysed for thirty (30) risk elements, which included Ag, As, B, Ba, Cd, Cu, Mo, Hg, Pb, Sb, Se and Zn at the SGS laboratory, Ghana, using Inductively Coupled Plasma Atomic Emission Spectrometry. Results showed that all the risk elements analysed were present in almost all the samples except Se, which was below the detection limit of <0.01mg/kg in all the WPCBs and As, Se, Sb, and Sn, in some WPHs. The average concentration of Cu (MPB - 1747.36 mg/kg; TVB - 2782.71 mg/kg; DCMB - 6506.00 mg/kg; RB - 4598.90 mg/kg; LMB - 14879.67 mg/kg) in all the boards exceeded the TTLC limit of 2500 mg/kg. Similarly, the average Pb concentrations detected in MPB (2168.73 mg/kg), TVB (4720.71 mg/kg), DCMB (2406.00 mg/kg) and RB (3189.00 mg/kg) exceeded the RoHS regulatory limit of 1000 mg/kg. With respect to the WPHs, none recorded values above the TTLC and RoHS limits. Overall, the wide range and concentration of valuable risk elements observed in WPCBs and WPH in this study suggest their potential for recovery as raw materials for the electronic industry. However, the high levels of Cu and Pd detected in the boards rendered them hazardous and required them to be managed by the mandatory hazardous waste handling protocol.

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Introduction

The electronics industry is the world's most significant, fastest-growing manufacturing industry (Liyakat & Liyakat, 2023). The increasing demand for newer and higher technological products, coupled with the high rate of obsolescence, accounts for this phenomenal growth. Consequently, large quantities of e-waste from computers, mobile phones, television sets (TVs), etc., are produced globally. This is evident in the estimated amount of 53.6 million metric tons (Mt) of e-waste generated in the year 2019, with an estimated yearly increment of 2 Mt (Forti et al., 2020). This phenomenon has compelled the need to recycle and reuse obsolete products. For instance, the European Union's Waste Electrical and Electronics Equipment (WEEE) Directive (WEEE Directive 2012/19/EU) mandates high collection, recovery, and recycling targets for end-of-life (EoL) electrical and electronic equipment (EEE) (Penttilä, 2020). This will minimize the 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 creates a five times lower environmental impact. It will also reduce the global demand for new metal production and the amount of material disposed of in landfills (Kumar et al., 2017).

Nonetheless, various directives are in place to ensure that the recycling of e-waste does not have adverse repercussions on human health and the environment due to the toxic substances present in e-waste (Maphosa & Mashau, 2020). Such Directives include the WEEE Directive, Directive 2011/65/EU, which restricts the use of certain hazardous substances in EEE, and specifies the maximum concentration limits for ten restricted materials, of which three are heavy metals: lead (Pb), mercury (Hg), and cadmium (Cd).

E-waste comprises components such as plastics and printed circuit boards (PrCBs). Plastic polymers are used as insulators and lightweight components in EEE, and their composition in WEEE ranges from 2.8 % to 72.3 %, depending on the type of electronic equipment (Lahtela et al., 2022). PrCB, the most precious component of e-waste, accounts for 3 to 6 wt% of the total e-waste (Wang et al., 2020). These materials contain a wide range of elements. It has been estimated that PrCBs contain about sixty elements (Force, 2009) categorised into metals, non-metals and organics (Szałatkiewicz, 2014). The metal components include iron (Fe), silver (Ag), nickel (Ni), antimony (Sb) and bismuth (Bi) (Goosey & Kellner, 2003). On the other hand, elements such as Pb, cadmium (Cd), chromium (Cr), mercury (Hg), bromine (Br) and tin (Sn) have been added to plastic polymers as pigments, fillers, UV stabilizers and flame retardants. Usually, these materials are added as compounds that often do not chemically bond with molecules of plastics but rather create a suspension in the solid plastic polymer (Nnorom & Osibanjo, 2009).

In Ghana, WPH and WPCB (after retrieving some metals, mainly copper) are unessential e-waste components and are either stored or scattered in the environment. However, these materials contain important elements (Maphosa & Mashau, 2023) that can be recovered and serve as raw materials in various industries, including the electronics sector. Nonetheless, these waste materials, when left in the environment, pose a threat to the economy, environment, and human health (Manikkampatt Palanisamy et al., 2022). For example, toxic chemicals such as Pb and Cd in these waste materials can be released into the environment (Donkor et al., 2017) and cause various health problems (Abubarkar et al., 2022), such as adverse neonatal health outcomes (Singh et al., 2021), lung function disorders, especially among children (Zeng et al., 2017), attention-deficit hyperactivity disorder

(ADHD) (Donzelli et al., 2019), and even cancers (Dutta et al., 2022). This study, therefore, aims to examine the content of some risk elements, including those imposed by RoHS restrictions, in waste WPCBs and WPHs of some common e-waste materials in Ghana, and determine their potential for recycling.

Materials and Methods

Sample collection and preparation

A total of forty-seven WPCBs and twenty-four 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, e-waste recycling sites, and workshops 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 2mm using a ceramic-coated cutting mill.

Sample Analysis

An amount of 0.5g 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: 0.02mg/kg - Ag, Al, Cr, Sb, Sn; 0.01mg/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; 0.1mg/kg - S.

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 were used. Sample blanks and duplicates were also used. All samples were analysed in duplicates.

Data Analysis

The experimental data obtained were evaluated by descriptive statistics 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. Tables 1A and 1B show 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 and 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). According to the study, WPCBs of TVs, laptop monitors, and mobile phones exhibited relatively pronounced concentrations of risk elements, whereas radio boards showed the lowest levels for most elements. This low concentration observed in the radio WPCBs results from their very nature, which is generally not as complicated as the 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 (within the magnitude of thousands) than those of Cd, molybdenum (Mo), and vanadium (V) (Tables 1A and 1B). The high levels of these elements indicate 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.

Comparing the results with the Total Threshold Limit Concentration (TTLC) limit, three elements, arsenic (As), copper (Cu), and Pb, were of much concern. The average concentration of Cu in all the boards exceeded the limit. A similar trend was observed for Pb except in LMB, whereas a large amount of As was observed only in MPB. Priya & Haiti (2017) also reported concentrations of Cu (201300mg/kg+400mg/kg) in laptop PrCBs and Pb (22600+800mg/kg) in TV PrCBs, both of which exceeded the TTLC limits. Sources of Pb in PrCBs include Pb soldering (Jha et al., 2012), while Cu is one of the significant components of bare boards of WPCBs (Anić-Vučinić et al., 2020). It is important to note that Cu levels in DCMB (6505.6 mg/kg) observed in this study were lower compared to other studies, such as Yamane et al., 2011; Kolias et al., 2014; Bizzo et al., 2014, who reported concentrations of 20190 mg/kg, 25014 mg/kg and 142000 mg/kg, respectively. On the contrary, 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.

Table 1A: 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, and nd: not detected.

Table 1B: 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, and nd: not detected.

Risk Elements Concentrations in Plastics Housing (PH)

The average concentrations of risk elements in eight different WPH samples of e-waste are shown in Tables 2A and 2B. All thirty elements analysed were detected in all the WPHs, except As, Be, B, Se and Sn, which were not detected in some cases. However, unlike the WPCBs, the concentrations of the various elements analysed were relatively lower. The result corroborated findings by Kolias et al. (2014). Aluminium, calcium (Ca), Cu, magnesium (Mg), sodium (Na), and phosphorus (P) were comparatively higher than the remaining elements. Calcium, one of the most abundant metals, had the highest mean element concentration. A significant source of calcium in e-waste plastics is calcium carbonate and calcium sulphate used as fillers to enhance the material's properties while reducing cost. Aluminium, on the other hand, was of higher concentrations in all samples except the calculator housing (295 mg/kg). Comparing the levels of metals obtained in the various WPHs, it was observed that the mean element concentrations in the TV plastic housing were the highest, followed by desktop computer housing and calculator housing, recording the least.

All the elements analysed in each WPH 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 are valuable sources of metals that can be extracted and used (Cayumil et al., 2014; Sahajwalla & Gaikwad, 2018). The valuable risk elements observed in this study attest to this fact. However, the recovery rate will depend on the method of extraction (Dutta et. al., 2018; Sahajwalla & Gaikwad, 2018). The study revealed that the traditional processing of metal extraction, which includes manual dismantling, open burning of WPCBs, and burning wires to recover Cu, among other methods, carried out in the country, is inappropriate and insufficient in retrieving all functional components, as many risk elements remain present, even after recycling. Apart from the environmental problems associated with this recycling method, when left in the environment, the elements in these materials have the potential to leach into the environment (Donkor et al., 2017; Sepúlveda et al., 2010), which can exacerbate the situation. According to Mao et al. (2020), the migration rate of heavy metals such as Cu and Pb in plastic accelerates with time.

Thus, to recover these essential elements, it is necessary to determine whether they comply with regulatory measures.

According to the Department of Toxic Substances Control (DTSC), the concentrations of extractable and non-extractable bio-accumulative or persistent toxic elements should not exceed the TTLC limit; otherwise, the substance is rendered hazardous (DTSC, 2005a). Comparing the results of the WPCBs and WPHs with the limit, the concentrations of Cu were found to be above the permissible limit for the former. In addition, Pb concentration in all the WPCB exceeded the RoHS limit except in the LMB.

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

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

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

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- 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

The high concentrations of risk elements (e.g., Pb and Cu) observed in e-waste materials (WPCBs) directly affect the recyclability and downstream utility of these materials. The presence of lead in WPCBs complicates both mechanical and thermal recycling (Li et al., 2024; Zhou & Qiu, 2010). High Pb content makes metal recovery via smelting riskier due to lead vapour emissions (Li et al., 2024; Song & Li, 2014), requiring stringent emission controls and worker protection measures. Crushing and separation of the WPCB may also result in the release of Pb into the environment (Zhou & Qiu, 2010).

Regarding these regulatory limits, once a particular metal fails, the entire material is considered hazardous (Okenwa-Ani et al., 2019) which disqualifies it for unrestricted recycling and triggers mandatory hazardous waste handling protocols. These protocols stipulate that waste should be handled only by authorised collectors, treatment, storage, and disposal facilities (EPA, 2018).

Conclusion

This study forms the basis and provides valuable insights into risk elements in WPCB and WPH. In general, WPCBs had higher levels of risk elements than the WPH. Cu levels in all five WPCBs exceeded the TTLC limit of 2500 mg/kg. Similar trends were noticed for Pb with respect to TTLC and RoHS limits (1000 mg/kg) except in the LMB. As far as the RoHS and TTLC regulatory limits are concerned, all the WPCB were hazardous and therefore must be managed under strict hazardous waste protocol. Further studies are required to ascertain the levels of risk elements in other components of e-waste, as well as the other types of waste electrical and electronic equipment, which were not considered in this study. In addition, it is important to ascertain the presence of other toxic substances such as BFRs, phthalates, and other organic toxicants in e-waste plastic housing materials and waste printed circuit boards, especially those classified under the Stockholm Convention POPs. Again, further research is needed to evaluate the economic feasibility of metal recovery from WPCBs and WPH using various extraction methods, such as hydrometallurgical, pyrometallurgical, or bioleaching methods, along with life-cycle assessments.

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