



Biomonitoring of metals in blood and urine of electronic waste (E-waste) recyclers at Agbogbloshie, Ghana

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HIGHLIGHTS

- e-waste workers are exposed to potentially high levels of diverse metals.
- Biomonitoring of technology critical and rare earth elements seldom done.
- Blood Pb, Sr, Tl and urinary Pb, Eu, La, Tb, and Tl higher in workers vs. controls.
- Exposures linked to different e-waste work practices.

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ABSTRACT

There is growing evidence that e-waste recyclers may be exposed to potentially high levels of metals though associations between such exposures and specific work activities is not well established. In addition, studies have focused on metals traditionally biomonitoring and there is no data on the exposure of recyclers to elements increasingly being used in new technologies. In the current study, levels of metals were measured in blood and urine of e-waste recyclers at Agbogbloshie (Ghana) and a control group. Blood and urine samples (from 100 e-waste recyclers and 51 controls) were analyzed for 17 elements (Ag, As, Ba, Cd, Ce, Cr, Eu, La, Mn, Nd, Ni, Pb, Rb, Sr, Tb, Tl, Y) using the ICP-MS. Most e-waste recyclers reported performing at least 4 different tasks in decreasing order as e-waste dismantling (54%), trading/selling of e-waste (45%), burning wires only (40%), and collecting wires after burning (34%). Mean levels of blood Pb, Sr, Tl, and urinary Pb, Eu, La, Tb, and Tl were significantly higher in recyclers versus controls. In general, the collectors and sorters tended to have higher elemental levels than other work groups. Blood Pb levels (mean 92.4 µg/L) exceeded the U.S. CDC reference level in 84% of the e-waste recyclers. Likewise, blood Cd, Mn, and urinary As levels in recyclers and controls were higher than in reference populations elsewhere. E-waste recyclers are exposed to metals traditionally studied (e.g., Pb, Cd, As) and several other technology-critical and rare earth elements which previously have not been characterized through human biomonitoring.

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1. Introduction

Increasing societal demands of electronic devices coupled with unsustainable disposal practices have made electronic waste (e-waste) one of the world's fastest-growing streams of solid-waste (Forti et al., 2020; Heacock et al., 2018; Miner et al., 2020; Tom & Rajan, 2020). Approximately 50 million tons of e-waste is currently generated each year across the world, and if left unchecked this is estimated to increase to 120 million tons per year by

the year 2050 (Julander et al., 2014; Platform for Accelerating the Circular Economy(PACE), 2019). Most (80%) of the e-waste processed worldwide is handled by the informal sector, and much of this work occurs in low- and middle-income countries where legal and policy frameworks are either non-existent or not enforced (Cazabon et al., 2017; Forti et al., 2020). The situation is further exacerbated given that informal recycling practices generally use crude and primitive methods thus resulting in sub-standard health and safety practices (T. Feldt et al., 2014; Nartey, 2016; Srigboh et al., 2016).

In Africa, one of the largest e-waste processing sites is located in Accra, Ghana. The “Agbogbloshie” scrap yard, for more than a decade, has served as a major e-waste processing site both nationally and globally and has provided employment opportunities for thousands of people (Basu et al., 2016; Daum et al., 2017; Srigboh et al., 2016). Furthermore, it has been estimated that e-waste activities contribute about 105–268 million US dollars to Ghana's economy, with most of this occurring at Agbogbloshie (EPA, 2013). Regardless of such economic benefits, processing of e-waste exposes recyclers to several potentially harmful chemicals (Chama et al., 2014; K. Grant et al., 2013; R. Grant and Oteng-Ababio, 2012; Laskaris et al., 2019; Srigboh et al., 2016). Notable chemicals, such as cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) may not only contaminate the workers but also be released into the environment where these may contaminate water bodies and food sources that local populations are reliant upon.

In recent years, studies have begun to characterize exposure of recyclers at Agbogbloshie to toxic elements. For example, Srigboh et al. (2016) sampled blood and urine from 58 male workers and found that their levels of blood cadmium and lead along with urinary arsenic were above reference guideline levels. In a study of 75 workers, Wittsiepe et al. (2017) found that levels of blood Pb, urine nickel (Ni) and urine chromium (Cr) were higher than values expected from background European populations. In a study of 84 workers, Yang et al. (2020) demonstrated that urinary arsenic levels exceeded the acceptable concentration in more than 80% of the participants. Taken together, these studies (among others) demonstrate that individuals working at Agbogbloshie are regularly exposed to a myriad of toxic metals and that the exposure levels for some elements are of health concern.

Human biomonitoring activities at e-waste sites tend to focus on commonly studied metals, though there are several other elements of concern, as recognized by groups such as the U.S. Agency for Toxic Substances and Disease Registry (ATSDR) (CDC, 2017; Henríquez-Hernández et al., 2017), that may be found in e-waste sites though are not well studied in terms of human exposures. Examples of such elements include barium (Ba), beryllium (Be), cobalt (Co), strontium (Sr), thallium (Tl), thorium (Th), uranium, (U), and vanadium (V). Some of these may be categorized as ‘technology-critical elements’ which represent a class of elements with increasing societal and economic interest given their essential roles in a range of existing and emerging technologies. Data concerning human exposures to many of these technology-critical elements (which also include some rare earth elements) is lacking, even though they are key components of many electronic items and of growing societal interest. To add to our understanding of exposures of e-waste recyclers at Agbogbloshie (Ghana) to a wider range of chemicals, the current study aimed to (i) measure levels of metals and technology-critical elements in whole blood and urine of e-waste recyclers and controls; (ii) compare levels of these metals across e-waste recycler work groups; and (iii) identify possible work-related and sociodemographic factors that may influence exposure levels. In doing so, this study extends upon previous works by drawing from a larger sample size, expanding the

number of elements analyzed, and incorporating a control population.

2. Materials and methods

2.1. Study population

Data for the current study was drawn from the GeoHealth-II longitudinal cohort study based in Accra, Ghana which was designed to focus on occupational and environmental hazards faced by e-waste recyclers who are near-exclusively adult males (Amoabeng Nti et al., 2020; Kwarteng et al., 2020; Laskaris et al., 2019). Here we focus on cross-sectional data collected from male e-waste recyclers (N = 100 from the Agbogbloshie site) and controls (N = 51 controls from Madina, a community about 20 km northeast of Agbogbloshie) sampled during in March 2017 as part of GeoHealth-II's first wave (see map in Supplemental Materials Figure SM1). To inform and familiarize eligible participants with the study's objectives and procedures, a community durbar (entry event) was held. Male adult e-waste recyclers who were aged 18 years and above and had worked at the e-waste site for at least six months were eligible for inclusion in this study. For the controls, they were recruited randomly from Madina, were matched to have similar socio-demographic characteristics as the e-waste recyclers (e.g., age, religion, dietary habits), and must have lived in that control region for at least six months. Briefly, research staff randomly selected domiciles in Madina, approached the household for an introductory discussion following which a brief screening questionnaire was administered to determine potential eligibility. We sought informed consent from all participants, and compensated them with 50 Ghanaian Cedis (approximately 10 USD, which is roughly an average day's wage), lunch, and a T-shirt. The study protocols were approved by the Institutional Review Boards at the University of Ghana, the University of Michigan and McGill University. In addition, the local chief of Agbogbloshie and Madina-Zongo allowed our research team to enter the community to conduct the study.

2.2. Sociodemographic and anthropometric measurements

Based on previous exposure assessments and occupational health surveys conducted at Agbogbloshie (Nti, 2015; Srigboh et al., 2016; Wittsiepe et al., 2017), a semi-structured questionnaire was developed, piloted, and used to collect information regarding participants' socio-demographic and work characteristics. Participant's height and weight were measured using a standardized protocol. Height was measured with a Seca stadiometer (Seca, Hamburg, Germany), and corrected to the nearest 0.1 cm, with participant standing upright on a flat surface without shoes, and the back of the heels and the occiput against the stadiometer (Alkhajah et al., 2012; Boateng, 2014; Zeba et al., 2014). Participant's bodyweight was measured and corrected to the nearest 0.1 kg using a portable Seca Scale (Seca770; Hamburg, Germany). The same model of a standard calibrated balance was used at both study sites.

2.3. Blood and urine sample collection

Blood and urine samples were collected by trained health professionals in clean and enclosed portable stations setup near each study site. Midstream urine samples (~15 mL) were collected into a plastic container at the start of each participant's visit typically between the hours of 9 a.m. to 4 p.m. Approximately 10 mL of blood was collected into a trace metal free BD Vacutainer tube with K₂EDTA, and placed on a blood tube roller (Micro-Teknik) for 5 min. Blood and urine samples were transported on dry ice to the

laboratory and then stored in a -80°C freezer until shipment to McGill University (Montreal, Canada) where they were stored frozen (-80°C) before analyses.

2.4. Metals analysis

Metals—namely, Cadmium (Cd), Arsenic (As); Lead (Pb), Manganese (Mn), and technology-critical elements such as Strontium (Sr), Silver (Ag), Cerium (Ce), Rubidium (Rb), Yttrium (Y), Europium (Eu), Lanthanum (La), Neodymium (Nd), Thallium (Tl) and Terbium (Tb) were analyzed in whole blood samples of participants. Also, levels of nickel (Ni), Chromium (Cr), Pb, Cd, As, Ag, Nd, Rb, La, Ba, Ce, Sr, Eu, Y, Nd, and Tb were measured in urine samples. Elemental levels were measured using the Inductively Coupled Plasma Mass Spectrometer (ICPMS; Varian 820MS). All tubes and pipette tips used were acid-washed (cleaned, soaked 24 h in 10% hydrochloric acid and rinsed 3 times in Milli-Q water) before usage. Matrix-specific reference materials (INSPQ; QM-B-Q1505 blood; QM-B-Q1506 blood; QM-B-Q1314 blood, QM-U-Q1109 urine) obtained from the Institut National de Santé Publique du Québec were used to gauge analytical accuracy. Not all elements we analyzed were covered by these reference materials, though we note that analytical standards were used for each element to derive standard curves and gauge recovery. Each batch run included replicate processing (i.e., digestion and ICPMS analysis) of every 12th sample to calculate analytical precision. Finally, procedural blanks were also included in each batch run from which the theoretical detection limit was determined for each element analyzed as three times the standard deviation of the mean blank value. We also note that the urinary data were not corrected for creatinine or specific gravity, and thus a limitation of this work.

2.5. Data analysis

Human biomonitoring data was initially analyzed using descriptive statistics. In the absence of suitable reference values for Ghanaians (or Africans), we mainly depended on established reference concentration ranges of metals from other studies. For this reason, reference levels or ranges of metals by Alimonti et al. (2005), the National Health and Nutrition Examination Survey (NHANES, 2011–2012), the Canadian Health Measures Survey 2007–2013, Iyengar and Woittiez (1988) and Hoet et al. (2013) were used for comparison.

Primary explanatory variables of interest included participant work status (e-waste recycler versus control), job task (dismantler, burner and collector/sorter), stress (self-reported), work characteristics such as daily duration (hours) of e-waste work activity and the number of years spent on this vocation and other socio-demographic factors such as educational status, daily income earned and age. Furthermore, environmental risk factors such as exposure to biomass burning, cigarette smoking, alcohol intake, and the body mass index (BMI) also served as exposures of interest.

Preliminary data analysis included tabulation of descriptive statistics for the sociodemographic and job characteristics. Differences in personal protective equipment (PPE) usage per job category were tested by the chi-square test. Next, the elemental levels were log-transformed prior to statistical analyses. As expected, most of the data (i.e. elemental levels) did not follow a normal distribution. Therefore, the comparison of elemental levels (both blood and urine) between e-waste recyclers and controls was performed using a non-parametric test (Wilcoxon rank-sum test). We again compared the differences in these levels among e-waste recycler groups using the Kruskal Wallis test. Next, Spearman's correlation tests were used to explore the correlation between

elements in blood and urine. Among the e-waste recyclers, the associations of work-related and sociodemographic factors and levels of blood and urinary elements were investigated using a linear regression model.

Outliers were identified as values that were more than three standard deviations away from the mean, and these were removed from the dataset. All values are reported as a mean (standard deviation) or a median (interquartile range) as stated. A p-value of 0.05 or lower was deemed significant, while in other cases a more restrictive p-value was used and indicated when making multiple comparisons.

3. Results

3.1. Socio-demographic characteristics of study population

Data regarding participants' age, daily income, marital status, education, religion, smoking, and alcohol status are summarized in Table 1. Compared to the controls, the e-waste recyclers were significantly younger and less educated. A quarter of e-waste recyclers reported having no formal education versus more than half of the controls who reported having completed senior secondary or higher education. The recyclers reported to work for approximately 9 h per day, and for about 10 years in this particular sector. More than half of the recyclers slept onsite, specifically inside their working shed located at the recycling area. More than half of the e-waste recyclers earned between 20 and 100 Ghana Cedis daily (~\$4 to 17 USD per day), while 24% of them reported to earning less than 20 Ghana Cedis per day. There were no significant differences between the two groups in terms of marital status, daily income earned, and alcohol use.

3.2. Work characteristics of E-waste recyclers

Before further categorization of job tasks, we examined the top 10 job categories and the frequency at which these tasks were executed (Table 2). Overall, most e-waste recyclers reported to have performed tasks from at least 4 job categories listed here in decreasing order of frequency: e-waste dismantling (54%) > trading/selling of e-waste (45%) > burning wires only (40%) > collection of wires after burning (34%). In addition to these tasks, the next most common activities reported to have been performed over the last three months included: burning of e-waste (34%), burning of wires (25%), removing covering off wires (10%), sorting e-waste (9%), and dismantling of e-waste equipment (6%). We also identified key activities such as dismantling and burning of e-waste were performed on average four days a week.

The job-tasks were collapsed into three main groups, namely burners, dismantlers, and collectors/sorters. Generally, 76% of e-waste recyclers admitted to regularly wearing any form of PPE. Specifically, more than half of the dismantlers used gloves (~51%) and rubber boots (~60%), while less than 50% of burners and collectors/sorters wore rubber boots during their work activities (Table 3). In terms of other basic PPE, such as dust masks/respirators, safety goggles/face shields and earplugs/earmuffs, less than 20% of burners, dismantlers and collectors/sorters self-reported wearing such items. Notably, we found that wearing PPE was significantly associated with a participant's income status ($\beta = 0.146$; 95% CI: 0.010, 0.283; $p = 0.04$). However, factors such as age, number of years spent recycling e-waste, hours spent per day recycling e-waste, educational status, religion, and job type were not associated with PPE use among the group of e-waste recyclers.

Table 1
Socio-demographic characteristics of e-waste recyclers and controls.

	Total N	E-waste recyclers n (%)	Controls n (%)	χ^2	p-value
Marital Status	150			4.43	0.06
Single		44(44.4)	31(60.8)		
Married		55(55.6)	20(39.2)		
Daily Income	149			5.12	0.16
≤GHS 20		24(24.2)	9(18.0)		
GHS 21–100		63(63.6)	30(60.0)		
GHS 101–200		8(8.1)	4(8.0)		
GHS >200		4(4.0)	7(14.0)		
Education	145			23.82	<0.01
None		25(25.2)	6(13.0)		
Primary		26(26.3)	4(8.7)		
Middle/JSS		32(32.3)	12(26.1)		
Secondary/SSS & Higher		16(16.2)	24(52.3)		
Religion	150			3.45	0.18
Muslim		92(92.9)	43(84.3)		
Christian		5(5.1)	7(13.7)		
Others		2(2)	1(2)		
Cigarette Smoking	146			4.52	0.03
Alcohol intake	151			0.01	0.92
Sleeping Place of e-waste recyclers	97				
On the site		54(55.7)			
Off site, but within 1 km of Agbogbloshie		35(36.1)			
More than 1 km away		8(8.2)			
Main Job-task of e-waste recyclers	100				
Burners		32(32)			
Dismantlers		49(49)			
Collectors/Sorters		19(19)			

Table 2
Self-reported job categories among the 100 male e-waste recyclers sampled from the Agbogbloshie e-waste recycling site (Accra, Ghana) in March 2017.

Task	Number recyclers who usually performed task	Number of hours performed task per day		Number of days performed task per week		Performed task during the past one month	Performed task during the past three months
	n (%)	Mean (SD)	Range	Mean (SD)	Range	n (%)	n (%)
Repair electronics	10 (10)	2.6 (1.7)	1–6 h	2.7 (1.8)	1–6 days	7 (4.7)	1 (0.7)
Collect or off-loading e-waste	33 (33)	4.3 (2.8)	1–13 h	3.7 (2.0)	1–7 days	13 (8.7)	8 (5.3)
Remove covering off wires	27 (27)	4.8 (2.8)	1–13 h	2.6 (2.0)	1–7 days	7 (4.7)	15 (10.0)
Dismantle e-waste equipment	58 (58)	2.3 (1.4)	1–6 h	4.0 (2.0)	1–7 days	51 (34.2)	9 (6.0)
Sort e-waste	29 (29)	2.0 (1.1)	1–5 h	2.6 (1.9)	1–7 days	13 (8.7)	14 (9.33)
Burn e-waste	21 (21)	3.4 (2.5)	1–9 h	4.2 (2.1)	1–6 days	1 (0.7)	51 (34.0)
Burn wires only	40 (40)	3.0 (2.9)	1–12 h	3.9 (2.2)	1–7 days	44 (29.5)	38 (25.3)
Ash/Wire collection after burning	34 (34)	1.8 (2.1)	1–11 h	3.3 (2.4)	1–7 days	12 (8.1)	1 (0.7)
Buying or trading e-waste	45 (45)	2.3 (2.7)	1–13 h	3.4 (2.2)	1–7 days	1 (0.7)	1 (0.7)
Smelt lead batteries	8 (8)	2.3 (1.1)	1–4 h	1.4 (0.7)	1–3 days	0 (0)	11 (7.3)

Table 3
Use of personal protective equipment (PPE) among e-waste recyclers according to three primary job tasks.

	Burners n (%)	Dismantlers n (%)	Collectors/Sorters n (%)	χ^2	p-value
Safety glasses, goggles, or face shields	4 (12.9)	2 (4.4)	2 (11.1)	1.97	0.37
Rubber-soled boots or shoes	14 (46.7)	23 (60.5)	7 (41.2)	2.24	0.33
Gloves	9 (30.0)	20 (51.2)	6 (42.9)	3.15	0.21
Dust mask or respirator	2 (6.7)	1 (2.7)	3 (17.7)	3.94	0.14
Long trousers	17 (56.7)	35 (89.7)	13 (76.5)	10.06	<0.01
Ear plugs or earmuffs	2 (6.7)	2 (5.4)	3 (17.7)	2.45	0.29
Helmets	0 (0)	2 (5.4)	2 (11.8)	3.37	0.19

3.3. Blood and urine biomonitoring data

The statistical distribution of metals in whole blood and urine samples of e-waste recyclers and controls is summarized in Table 4. Summary of blood and urinary elemental biomarker quality control (QC) measures are reported in Supplemental Materials (Tables SM1 and SM2, respectively).

The mean blood levels of Pb, Sr and Tl were significantly higher among the e-waste recyclers compared to the controls (Table 4;

Supplemental Materials Figure SM2). On the other hand, mean blood levels of other elements (e.g., Cd, Mn, Y, Eu, and Tb) were higher in controls than the e-waste recyclers. Urinary levels of Pb, Eu, La, Tb, and Tl were higher in e-waste recyclers than controls (Table 4; Supplemental Materials Figure SM3). Notable was that urinary As levels were higher in controls than the e-waste recyclers.

Metal levels in e-waste recyclers were compared across the three primary job-tasks (Table 5; Supplemental Materials Figures SM4 and SM5). Urinary levels of As, Ba and Tb were highest

Table 4

Summary of elemental levels ($\mu\text{g/L}$) in blood and urine of e-waste recyclers and controls. Graphical representations of this blood and urine data are in Supplemental Materials (Figures SM1 and SM2, respectively).

Elements	E-waste recyclers		Controls		p-value
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)	
Whole Blood					
Pb	92.35 ± 63.69	76.82 (49.37)	40.67 ± 19.12	40.25 (17.45)	<0.01
Cd	0.73 ± 0.55	0.59 (0.43)	0.93 ± 0.64	0.81 (0.55)	<0.01
Mn	12.74 ± 5.09	12.56 (7.15)	15.54 ± 5.16	14.71 (7.69)	<0.01
Rb	2497.59 ± 573.80	2525.53 (691.85)	2561.96 ± 659.09	2543.11 (992.71)	0.60
Ce	0.16 ± 0.19	0.10 (0.08)	0.47 ± 0.85	0.06 (0.12)	<0.01
Sr	50.25 ± 18.65	48.84 (23.24)	41.56 ± 12.48	38.90 (19.12)	<0.01
Eu	0.018 ± 0.006	0.015 (0.005)	0.023 ± 0.010	0.020 (0.005)	<0.01
Y	0.05 ± 0.05	0.03 (0.03)	0.13 ± 0.19	0.05 (0.06)	<0.01
La	0.51 ± 0.59	0.34 (0.27)	0.61 ± 0.78	0.27 (0.21)	0.06
Nd	0.09 ± 0.06	0.07 (0.05)	0.20 ± 0.32	0.07 (0.04)	0.10
Tl	1.81 ± 0.56	1.73 (0.69)	1.14 ± 0.30	1.09 (0.24)	<0.01
Tb	0.01 ± 0.005	0.01 (0.005)	0.02 ± 0.01	0.02 (0.003)	<0.01
Urine					
Pb	7.76 ± 4.87	6.89 (5.22)	4.06 ± 4.45	3.42 (2.37)	<0.01
Cd	0.68 ± 1.18	0.38 (0.56)	0.50 ± 0.35	0.42 (0.44)	0.88
As	58.75 ± 59.45	42.90 (57.07)	90.55 ± 66.02	69.53 (101.08)	<0.01
Ag	1.17 ± 5.03	0.03 (0.04)	4.83 ± 11.84	0.04 (0.11)	0.07
Tb	0.05 ± 0.06	0.03 (0.05)	0.02 ± 0.01	0.02 (0.01)	<0.01
Nd	0.13 ± 0.35	0.07 (0.05)	0.06 ± 0.05	0.06 (0.02)	<0.01
Rb	1544.42 ± 986.14	1392.76 (1245.84)	1709.07 ± 1352.01	1439.33 (1245.57)	0.67
La	0.57 ± 0.56	0.48 (0.23)	0.39 ± 0.52	0.24 (0.09)	<0.01
Ba	37.51 ± 85.68	7.25 (37.00)	11.04 ± 38.35	3.90 (2.55)	<0.01
Ce	0.33 ± 0.71	0.15 (0.19)	0.15 ± 0.17	0.09 (0.07)	<0.01
Sr	225.10 ± 203.14	188.12 (232.45)	222.21 ± 143.52	190.87 (198.52)	0.58
Eu	0.03 ± 0.09	0.02 (0.01)	0.01 ± 0.01	0.01 (0.01)	<0.01
Y	0.10 ± 0.41	0.04 (0.03)	0.05 ± 0.07	0.03 (0.03)	0.10
Cr	11.48 ± 21.55	8.14 (4.64)	11.55 ± 28.46	7.93 (3.43)	0.31
Ni	18.24 ± 43.66	9.07 (10.18)	9.34 ± 11.74	6.93 (5.61)	0.08
Tl	11.50 ± 5.98	11.53 (9.47)	8.91 ± 3.26	9.23 (3.92)	0.02

in collectors/sorters, followed by dismantlers and then burners. For other urinary elements (i.e., Ba, Cr and Y), levels were highest among dismantlers followed by collectors/sorters and burners. Although not statistically significant, blood levels of Pb was highest amongst the dismantlers, whereas Cd in blood was highest among the collectors/sorters.

3.4. Correlation between blood and urinary metals

This study also examined the associations between blood and urinary metals in the e-waste workers using Spearman's correlations (Supplemental Materials Tables SM3, SM4, SM5). We found multiple significant correlations between metals in the blood (26/66 possible binary combinations were significant), urinary metals urinary (51/105 possible binary combinations were significant) as well as metals in blood versus urine (37/180 possible binary combinations were significant). In urine, metals such as Cd, Pb, Tb, Nd, Rb, Ba, Ce, Eu and Ni were found to be positively correlated with more than three other metals analyzed. In addition, we note that metals such as Pb, Mn, Eu, Rb, Tb, Y, and Ce were positively correlated to at least two or more metals in blood.

3.5. Relationships between job-related factors and biomonitoring data

Using simple regression analyses, 13 job-related factors were found to be significantly related to blood metal levels of e-waste recyclers (Supplemental Material Table SM6). Among these factors, cigarette smoking ($\beta = 0.81$; 95% CI: 0.47, 1.12; $p < 0.01$) and age ($\beta = 0.03$; 95% CI: 0.01, 0.06; $p = 0.01$) were significantly associated with increases in blood Cd levels. Exposure to biomass burning was associated with reductions in their blood levels of Mn ($\beta = -0.26$;

95% CI: $-0.44, -0.09$; $p = 0.004$) and Rb ($\beta = -0.16$; 95% CI: $-0.30, -0.01$; $p = 0.03$). Blood levels of Tl ($\beta = 0.19$; 95% CI: 0.05, 0.32; $p = 0.003$) and Tb ($\beta = 0.20$; 95% CI: 0.05, 0.35; $p = 0.01$) were related with self-reported job tasks. Factors, such as number of years spent recycling e-waste and stress (self-reported) were associated with increases in blood La levels, and the daily hours spent recycling e-waste was positively related with increases in blood Sr of recyclers. Factors such as alcohol intake contributed to the elevated levels of Ag in the blood of the recyclers. BMI and the usage of PPE were unrelated to elemental levels measured in e-waste recyclers ($p > 0.05$). Furthermore, the number of years spent informally recycling e-waste was associated with significant increases in the amount of Sr excreted in urine of e-waste recyclers ($\beta = 0.06$; 95% CI: 0.002, 0.11; $p = 0.04$). Cigarette smoking was also associated with the significant reductions in Ba ($\beta = -0.90$; 95% CI: $-1.74, -0.07$; $p = 0.04$) and Sr ($\beta = -0.846$; 95% CI: $-1.33, -0.23$; $p = 0.01$) levels excreted in urine.

4. Discussion

The environmental public health concerns at informal e-waste recycling sites like Agbogbloshie are well-known and have tended to focus on metals traditionally biomonitoring such as Pb, As, and Cd. While studies are needed to better resolve exposures to these well-studied metals, there is an unmet need to expand biomonitoring efforts to increase the number of elements studied especially emerging ones that may be classified as technology-critical and/or rare earth. Therefore, the current study investigated blood and urinary levels of metals typically biomonitoring along with novel and understudied technology-critical elements in a study population, while also ensuring a higher sample size than past efforts as well as matched controls. In doing so, we add

Table 5

Elemental levels ($\mu\text{g/L}$) in blood and urine according to e-waste recycler self-reported primary job classification. Graphical representations of this blood and urine data are in Supplemental Materials (Figures SM3 and SM4, respectively).

Element	Burner (n = 32)		Dismantler (n = 49)		Collector/Sorter (n = 19)		Kruskal Wallis Test	p-value
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)		
Whole Blood								
Pb	82.56 ± 37.49	67.35 (38.44)	98.75 ± 75.50	77.04 (56.18)	92.29 ± 66.38	83.34 (50.3)	0.78	0.68
Cd	0.68 ± 0.51	0.56 (0.50)	0.74 ± 0.51	0.61 (0.39)	0.78 ± 0.69	0.58 (0.42)	0.32	0.85
Mn	11.28 ± 5.38	11.59 (6.99)	13.71 ± 4.77	12.90 (6.01)	13.05 ± 4.88	13.50 (6.86)	3.98	0.14
Rb	2327.38 ± 589.86	2343.56 (596.83)	2539.79 ± 527.00	2600.82 (707.10)	2675.44 ± 617.49	2708.18 (645.42)	5.35	0.07
Ce	0.13 ± 0.22	0.09 (0.07)	0.16 ± 0.18	0.10 (0.08)	0.21 ± 0.19	0.14 (0.13)	5.89	0.05
Sr	52.52 ± 24.35	48.60 (27.69)	48.38 ± 15.89	8.86 (21.51)	51.23 14.59	46.36 (20.45)	0.29	0.86
Eu	0.016 ± 0.007	0.015 (0.010)	0.019 ± 0.006	0.018 (0.005)	0.019 ± 0.050	0.020 (0.010)	7.19	0.02
Y	0.05 ± 0.08	0.03 (0.02)	0.04 ± 0.03	0.03 (0.03)	0.05 ± 0.04	0.05 (0.04)	4.43	0.11
La	0.39 ± 0.24	0.29 (0.21)	0.54 ± 0.78	0.33 (0.26)	0.61 ± 0.39	0.46 (0.39)	9.355	<0.01
Nd	0.07 ± 0.04	0.07 (0.03)	0.09 ± 0.07	0.07 (0.04)	0.10 ± 0.05	0.09 (0.06)	4.63	0.10
Tl	1.47 ± 0.43	1.51 (0.44)	1.98 ± 0.51	1.94 (0.70)	1.93 ± 0.68	1.97 (0.91)	18.64	<0.01
Tb	0.011 ± 0.004	0.010 (0.005)	0.013 ± 0.005	0.010 (0.005)	0.014 ± 0.006	0.015 (0.010)	6.91	0.03
Urine								
Pb	7.23 ± 3.66	6.97 (5.05)	7751 ± 5.08	6.89 (4.81)	8.66 ± 6.11	6.60 (7.24)	0.19	0.91
Cd	0.53 ± 0.65	0.31 (0.35)	0.80 ± 1.60	0.45 (0.52)	0.62 ± 0.42	0.51 (0.45)	4.49	0.11
As	40.32 ± 32.80	31.41 (38.20)	60.21 ± 42.36	46.74 (72.61)	86.16 ± 105.86	56.60 (72.36)	5.93	0.05
Ag	2.89 ± 8.57	0.03(0.03)	0.27 ± 0.69	0.03 (0.04)	0.51 ± 0.93	0.05 (0.15)	1.85	0.40
Tb	0.03 ± 0.03	0.02 (0.03)	0.06 ± 0.08	0.04 (0.04)	0.06 ± 0.05	0.06 (0.06)	6.55	0.04
Nd	0.08 ± 0.04	0.07 (0.03)	0.12 ± 0.20	0.07 (0.06)	0.26 ± 0.73	0.08 (0.04)	4.64	0.10
Rb	1558.85 ± 1020.10	1518.38 (1692.71)	1561.62 ± 986.04	1399.47 (1335.09)	1477.57 ± 978.68	1340.15 (907.34)	0.12	0.94
La	3.41 ± 0.00	3.41 (0.00)	3.41 ± 0.00	3.41 (0.00)	3.41 ± 0.00	3.41 (0.00)	9.84	<0.01
Ba	10.30 ± 14.28	4.01 (5.51)	56.95 ± 118.61	8.05 (37.87)	35.25 ± 0.81	39.71(35.35)	9.39	<0.01
Ce	0.18 ± 0.13	0.15 (0.19)	0.27 ± 0.43	0.14 (0.18)	0.75 ± 1.40	0.20 (0.36)	9.18	0.01
Sr	236.80 ± 265.70	191.00 (214.14)	201.14 ± 142.60	178.67 (208.38)	264.67 ± 213.15	195.36 (277.21)	1.19	0.55
Eu	0.013 ± 0.007	0.010 (0.005)	0.041 ± 0.131	0.015 (0.010)	0.030 ± 0.045	0.015 (0.008)	7.46	0.02
Y	0.045 ± 0.026	0.038 (0.025)	0.076 ± 0.121	0.040 (0.035)	0.298 ± 0.898	0.050 (0.050)	5.96	0.04
Cr	9.13 ± 9.82	6.32 (5.69)	9.41 ± 6.86	8.24 (3.22)	20.54 ± 45.93	8.92 (7.63)	6.89	0.03
Ni	10.91 ± 18.33	7.59 (1.72)	17.52 ± 30.67	9.96 (10.67)	32.35 ± 83.57	9.28 (21.65)	3.71	0.16
Tl	8.57 ± 4.50	7.66 (7.34)	13.18 ± 6.53	13.66 (9.89)	12.28 ± 5.06	11.22 (9.63)	11.45	<0.01

knowledge to our past studies at Agbogbloshie (Akormedi et al., 2013; Asampong et al., 2015; Torsten Feldt et al., 2014; Laskaris et al., 2019; Srigboh et al., 2016; Wittsiepe et al., 2017) while also contributing valuable information to the broader community (e.g., new elements biomonitoring, use of a matched control population, associations between work practices and human biomonitoring data studied).

The unsafe and poor working conditions of informal e-waste recycling workers is still prevalent at Agbogbloshie (Akormedi et al., 2013; Basu et al., 2016; Srigboh et al., 2016). Most e-waste recyclers use crude and physical methods of recycling (e.g. open-air burning of waste, chiselling or hammering open electronics) to isolate valuable metals, without appropriate use of PPE. Following our past work at Agbogbloshie in which we focused on 9 key job activities (Srigboh et al. (2016)), here we categorized recyclers into 10 different job tasks. We further grouped the recyclers into three principal groups (burners, dismantlers and collectors/sorters) to better understand how the biomonitoring data could be related with specific e-waste activities undertaken. While there were some differences in the biomonitoring data between these work groups, we do note that many of the workers performed multiple tasks making it difficult to associate specific work tasks with elements biomonitoring. Consistent with previous findings, we found limited use of PPE (such as dust mask/respirator, safety goggles/face shields, and earplugs/earmuffs) among e-waste recycler groups (burners, dismantlers and collectors/sorters).

Our findings here, when coupled with past studies at Agbogbloshie, provide a strong weight of evidence that both the e-waste recyclers and the control population are exposed to a range of metals as well as technology-critical elements, with some cases of values exceeding health guidelines or reference ranges. However, given that we are not aware of biomonitoring studies that have

properly established reference levels for the Ghanaian (or more broadly, African) population, proper external validation cannot be realized. Nonetheless, we focused our comparisons with biomonitoring reference levels from developed countries, past studies at Agbogbloshie, as well as between the e-waste recyclers and the control group.

In Agbogbloshie, several elements (such as Pb, As, Cd, Ag, Ni, Mn) studied here were previously measured in the blood and urine of e-waste recyclers (Brigden et al., 2008; Srigboh et al., 2016; Wittsiepe et al., 2017; Yang et al., 2020). Here we focus our discussion on four metals that are of greatest health concern to many populations that also tend to be biomonitoring frequently (blood Pb, Cd and Mn, and urinary As). For example, Srigboh et al. (2016) measured relatively high levels of Pb (mean 79.3 $\mu\text{g/L}$) in blood of e-waste recyclers at Agbogbloshie from April 2014. Subsequently, Wittsiepe et al. (2017) also found similarly elevated blood Pb levels (mean 101.9 $\mu\text{g/L}$) among e-waste recyclers at Agbogbloshie compared to a control population (44.3 $\mu\text{g/L}$: mean) that lived in a suburb near the controls used in the current study. In the current study, blood Pb levels in the e-waste recyclers (92.4 $\mu\text{g/L}$) and controls (40.7 $\mu\text{g/L}$) were similar to these previous ones. Furthermore, blood Pb levels in e-waste recyclers were independent of their job-task undertaken, suggesting that Pb is a common contaminant at Agbogbloshie, and the fact that recyclers are often involved in multiple tasks (Adusei et al., 2020; Burns et al., 2019; Laskaris et al., 2019; Srigboh et al., 2016). Such is not surprising as there are estimates that Pb occurs in relatively large amounts in e-waste that is shipped, sorted, dismantled and burnt at Agbogbloshie (Kumi et al., 2019; Platform for Accelerating the Circular Economy(PACE), 2019). Finally, 84% of the e-waste recyclers sampled here had blood Pb levels that were above U.S. CDC/NIOSH reference level of 50 $\mu\text{g/L}$ (or widely reported as 5 $\mu\text{g/dL}$) thus

reinforcing needs for follow-up health studies.

In terms of blood Cd levels (recyclers: 0.73 $\mu\text{g/L}$ versus control: 0.93 $\mu\text{g/L}$), the mean values are slightly higher to those measured previously by Wittsiepe et al. (2017) on their study of Agbogbloshie recyclers (0.55 $\mu\text{g/L}$) and controls (0.57 $\mu\text{g/L}$), though lower than the study by Srigboh et al. (2016) that reported a mean level of 1.7 $\mu\text{g/L}$. These data suggest no difference in Cd exposure between e-waste recyclers and the general population though we note that the values reported here in the recyclers and controls are 3.1 and 4.0-fold, respectively, higher than average values for males sampled during the 2013–2014 cycle of the U.S. National Health and Nutrition Examination Survey (NHANES) and around the 90th percentile value.

We also focused on urinary As, and found higher levels in the controls (69.3 $\mu\text{g/L}$) compared to the e-waste recyclers (42.9 $\mu\text{g/L}$). These urinary As values are lower than mean levels previously reported by Srigboh et al. (2016) from their study on male workers at Agbogbloshie (77.5 $\mu\text{g/L}$) though there is good overlap in the ranges of both studies. In the current study we note that the measured values of urinary As are much higher than average levels in the U.S. (6.3 $\mu\text{g/L}$ in males 20 years and older; 2013–2014 cycle of the U.S. National Health and Nutrition Examination Survey (NHANES), and that 37% of control population and 17% of the recyclers had levels exceeding 100 $\mu\text{g/L}$, a value reported by the U.S. Agency for Toxic Substances and Disease Registry (ATSDR, 2007) to be of possible health concern. Given that the location of the control population (Madina-Zongo) is far removed from the e-waste recycling site, the higher As levels measured may be attributed to their drinking water source, consumption of possible As-contaminated foods and exposure to vehicular emissions. A previous study on the background population in Accra found urinary As levels to be relatively high with a geometric mean of 147 $\mu\text{g/L}$ (Asante et al. (2012). A finding as such demonstrates that chemical exposures among recyclers at Agbogbloshie is relatively high, but that coupled with other studies (Daum et al., 2017; Fierens et al., 2016; Wittsiepe et al., 2017) exemplifies that exposures to certain chemicals can be equally high in other parts of Accra thus supporting the need for biomonitoring efforts that aim to increase understanding of background populations.

We also focused our analysis of blood Mn levels, and found that mean levels in the e-waste recyclers (12.7 $\mu\text{g/L}$) were lower than in the controls (15.6 $\mu\text{g/L}$). These values are slightly higher than levels reported in a past study of e-waste recyclers at Agbogbloshie (9.8 $\mu\text{g/L}$; Srigboh et al. (2016) though much higher than levels reported in Austria of municipal incinerator plant recyclers (mean: 0.46 $\mu\text{g/L}$) (Wultsch et al., 2011). The blood Mn levels reported here in the recyclers and controls are 1.4 and 1.7-fold, respectively, higher than average values for males sampled during the 2013–2014 cycle of the U.S. National Health and Nutrition Examination Survey (NHANES) and around the 90th percentile value of the U.S. population. Possible sources of Mn exposure may include food, water, dust, and fumes produced by industrial processes (chemical and steel industries, dry battery manufacture, and methyl cyclopentadienyl manganese tricarbonyl (MMT)) have been documented (ATSDR, 2012; Bena et al., 2020).

In addition to studying metals that are classically investigated at e-waste sites, to our knowledge this is the first study to report comprehensively upon levels of multiple technology-critical elements in blood and urine of e-waste recyclers. There are few biomonitoring studies on these elements for us to draw meaningful comparisons with. A pilot cross-sectional study by Hao et al. (2015) measured urinary levels of technology-critical elements like La (0.101 $\mu\text{g/L}$), Ce (0.138 $\mu\text{g/L}$), Nd (0.181 $\mu\text{g/L}$), and Y (0.092 $\mu\text{g/L}$) of an adult population in a mining area in China (Hao et al., 2015). In the current study, the median urinary La (3.4 $\mu\text{g/L}$) levels in the e-

waste recyclers were much higher than the levels reported by Hao et al. (2015) while the urinary Nd and Y levels reported by Hao et al. (2015) were twice higher than the median values we report here. We are not aware of urinary reference ranges for technology-critical elements like Ce, Eu, La, Nd, Rb, Tb, and Y to draw comparisons with, and thus more work is needed to increase understanding of human exposures to such elements. Nonetheless, we do note that we were able to measure these elements in the blood and urine of the study participants (both e-waste workers and controls).

5. Conclusions

Environmental health concerns at e-waste recycling sites have largely focused on metals traditionally biomonitoring (e.g., Pb, As, Cd, Mn). In the current study we help better resolve human exposures to these well-studied metals, but also expand our understanding of human exposures to a number of other elements including emerging ones that may be classified as technology-critical and/or rare earth. We found that blood Pb levels exceeded the U.S. CDC reference level in 84% of the e-waste recyclers. Likewise, blood Cd, Mn, and urinary As levels in recyclers and controls were higher than in reference populations elsewhere. Further, we compared levels across e-waste recycler work groups, and identified possible work-related and sociodemographic factors that may influence exposure levels. We found that most e-waste recyclers performed at least 4 tasks, and that this made it difficult to associate specific tasks with concentrations of elements biomonitoring. Mean levels of blood Pb, Sr, Tl, and urinary Pb, Eu, La, Tb, and Tl were significantly higher in recyclers versus controls. In general, the collectors and sorters tended to have higher elemental levels than other work groups.

There are a number of strengths associated with our work, and also recommendations for new studies moving forward. To our knowledge, the sample size of the current biomonitoring study is one of the largest of its kind at Agbogbloshie (and other e-waste sites worldwide), though it captures only 2–4% of the estimated workforce. In addition, this study is the first to biomonitor exposures to technology-critical element levels (including rare earth elements) among e-waste recyclers in Ghana (and likely worldwide). Moving ahead, there is a need to derive reference biomonitoring data from Ghanaian (and African) populations for classically studied metals as well as emerging ones from which valid comparisons can be made. While at Agbogbloshie there have been many studies, there is still a need for studies that characterize exposures over time as past surveys at Agbogbloshie have always been cross-sectional (Torsten Feldt et al., 2014; Srigboh et al., 2016; Wittsiepe et al., 2017). Additionally, studies should characterize target chemicals in the broad environment (e.g., food, water, soil) at Agbogbloshie to help increase understanding of source-exposure pathways. Further to this, steps need to be taken in future studies to better link the biomonitoring data with exposure sources both at the work site but also the larger area (e.g., road traffic, biomass burning) so that interventions may be properly designed. Finally, there is a dearth of research on how multiple elemental exposures (especially as mixtures) associate with health status in e-waste recyclers without which associated risks cannot be estimated. All of these studies will not only increase our understanding more holistically of the situation at Agbogbloshie but also help inform intervention activities.

The data here support past studies from Agbogbloshie (and elsewhere) that e-waste recyclers are exposed to relatively high levels of classically studied toxic metals such as Pb, As, and Cd. The work here also contributes to the limited information available regarding exposure of e-waste recyclers to an expanded number of metals including many technology-critical elements. While there

were some differences between the recyclers and controls here, exposure to these elements appears widespread across the city of Accra. Though higher levels of Pb, Sr, Tl, and Ce were measured in e-waste recyclers, other elements like Cd, As, Mn and several technology-critical elements were measured at higher levels in the blood and urine of controls.

Authors' contributions

Sylvia A. Takyi: Conceptualization, Investigation, Methodology, Laboratory and formal analysis, Writing – original draft, Data curation, Reviewing and editing. Niladri Basu: Conceptualization, Writing – original draft, Laboratory analysis, Methodology, Data curation, Reviewing and editing, Supervision, Funding acquisition, Writing – original draft preparation. John Arko-Mensah: Investigation, Reviewing and editing, Supervision, Methodology, Writing – original draft. Duah Dwomoh: Formal analysis, Visualization, Reviewing and editing. Karel G. Houessionon: Laboratory analysis, Reviewing and editing. Julius N Fobil: Conceptualization, Resources, Supervision, Funding acquisition, Project administration, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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