



Multiple elemental exposures amongst workers at the Agbogbloshie electronic waste (e-waste) site in Ghana



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HIGHLIGHTS

- Agbogbloshie is one of the world's largest electronic waste recycling sites.
- Little is known about human exposures to toxic elements at the site.
- We measured As, Cd, Cr, Co, Cu, Fe, Pb, Mn, Hg, Ni, Se, Zn in 69 workers.
- Cadmium, lead, and arsenic levels were of concern.

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ABSTRACT

Electronic waste (e-waste) recycling is growing worldwide and raising a number of environmental health concerns. One of the largest e-waste sites is Agbogbloshie (Ghana). While several toxic elements have been reported in Agbogbloshie's environment, there is limited knowledge of human exposures there. The objectives of this study were to characterize exposures to several essential (copper, iron, manganese, selenium, zinc) and toxic (arsenic, cadmium, cobalt, chromium, mercury, nickel, lead) elements in the urine and blood of male workers ($n = 58$) at Agbogbloshie, as well as females ($n = 11$) working in activities that serve the site, and to relate these exposures to sociodemographic and occupational characteristics. The median number of years worked at the site was 5, and the average worker indicated being active in 6.8 tasks (of 9 key e-waste job categories). Additionally, we categorized four main e-waste activities (in brackets % of population self-reported main activity): dealing (22.4%), sorting (24.1%), dismantling (50%), and burning (3.4%) e-waste materials. Many blood and urinary elements (including essential ones) were within biomonitoring reference ranges. However, blood cadmium (1.2 $\mu\text{g/L}$ median) and lead (6.4 $\mu\text{g/dl}$; 67% above U.S. CDC/NIOSH reference level), and urinary arsenic (38.3 $\mu\text{g/L}$; 39% above U.S. ATSDR value) levels were elevated compared to background populations elsewhere. Workers who burned e-waste tended to have the highest biomarker levels. The findings of this study contribute to a growing body of work at Agbogbloshie (and elsewhere) to document that individuals working within e-waste sites are exposed to a number of toxic elements, some at potentially concerning levels.

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1. Introduction

The recycling of electronic waste (e-waste) is proliferating in many regions of the world. Around 41.8 million tons (Mt) of e-waste

was generated globally in 2014, and this number is expected to grow (Baldé et al., 2014). While e-waste can be efficiently recycled domestically in high-income countries, a large amount is being transported to low- and middle-income countries where the recycling practices are informal and generally unregulated (Brigden et al., 2008). In Ghana secondhand electrical and electronic equipment imports such as mobile phones, television sets, computers, stereos and radios frequently come from Europe and North America, and this flow of equipment has increased by nearly a

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factor of 3 between 2003 and 2008 (Amoyaw-Osei et al., 2011). While some this equipment can be sold for reuse, not all of the devices imported during this time were useful. For example, approximately 30–40% of all electronics imported into Ghana were non-functional (Amoyaw-Osei et al., 2011; Schluep et al., 2011), and of these approximately 50% were repaired locally and sold, while the other 50% was deemed unusable and became designated as e-waste, which amounted to approximately 40,000 tons of imported e-waste in 2010 (Schluep et al., 2011).

One of the largest and most publicized e-waste sites in the world is located in Ghana's capital city of Accra. The site, known as Agbogbloshie, originated as a scrap metal recycling site and over the past decade has grown to serve as an important recycling site for e-waste (Amoyaw-Osei et al., 2011). In recent years Agbogbloshie has come under media scrutiny due to the negative health and safety conditions at the site. In 2013, the site was ranked among the world's top ten toxic threats by the Blacksmith Institute and Green Cross Switzerland (Bernhardt and Gysi, 2013).

Worldwide there is growing concern about exposures to toxic chemicals and the associated health impacts at e-waste recycling sites (Heacock et al., 2016), and Agbogbloshie is no exception. At Agbogbloshie, toxic elements arising from the electronic items that are processed, including (but not limited to) arsenic, lead, mercury and copper, have been found in soil, water, ash, sediment and dust collected from the site (Otsuka et al., 2012; Atiemo et al., 2012; Brigden et al., 2008; Chama et al., 2014; Itai et al., 2014). The area is thus characteristic of a toxic waste site, and while a number of relevant human exposure pathways exist little is known about exposure of workers and community residents to these elements. A limited study by Asante et al. (2012) of urine samples from 20 male workers from Agbogbloshie documented that some elemental exposures were elevated. However, a more in depth study is needed to better characterize elemental exposures, relate these exposures with key sociodemographic variables, and determine which e-waste activities pose the greatest exposure risks for workers at Agbogbloshie so as to help inform future actions. Here, the objective of the study was to characterize exposures to several essential (copper, iron, manganese, selenium, zinc) and toxic (arsenic, cadmium, cobalt, chromium, mercury, nickel, lead) elements in the urine and blood of male workers at the Agbogbloshie site, as well as females who sell water and food at the site, and to relate these exposures to a number of sociodemographic and occupational characteristics.

2. Materials and methods

2.1. Study site description

The Agbogbloshie e-waste recycling site is situated on the bank of the Korle-lagoon on the western side of the Odaw River in central Accra, Ghana (Amoyaw-Osei et al., 2011). The area is flat and highly industrialized and urbanized, consisting of scattered recyclers working out of small sheds and in the open. An assortment of electronic items, namely refrigerators, computers, and car parts (as well as other industrial and residential items) are transported to the site for processing. It is important to note that workers at the site not only recycle e-waste, but also other items such as scrap metal, so it is not easy to distinguish among these activities. The scrap metal section at Agbogbloshie is separated into two main areas. In the first area, items are offloaded, collected, sorted, dismantled, and traded. The workers use the second area, located at the edge of the Odaw River, as an operational field for the creation of small fires (fueled by scrap rubber tires, foam insulation, and other debris) that are used to burn plastics off of electronic wires and coils to retrieve the metals of interest. The residential community that houses

Agbogbloshie workers and their families (as well as others from the general population) is located east of the e-waste recycling site, about 100 m across the Odaw River.

2.2. Participants and samples

In brief, and as outlined in our past studies at Agbogbloshie (Wittsiepe et al., 2015; Feldt et al., 2014; Akormedi et al., 2013; Asampong et al., 2015; Burns et al., 2016), a community entry activity facilitated by the Greater Accra Scrap Dealers Association took place to notify and familiarize the workers with the study's purpose and procedures. Inclusion criteria for participation in the study were age greater than or equal to 18 years old, and involvement in the e-waste recycling process for least the previous six months. Participants represented a convenience sample of available workers; an estimated 4500 to 6500 individuals work at Agbogbloshie (Prakash et al., 2010). All procedures and objectives for the study were explained to each participant in English and the local languages (via hired translators) and informed consent was obtained. In total, 69 participants were recruited into this study (58 male e-waste workers, and 11 females who service the site by selling food and water) in April 2014. Participants were compensated for their involvement with a small monetary gift (10 Ghana cedis or roughly \$3USD) and a meal. Institutional Review Board (IRB) approval for this work was obtained from the Noguchi Memorial Institute for Medical Research (NMIMR) - University of Ghana (IRB00001276) and the University of Michigan (HUM00028444).

Participants were transported to a local health clinic for interviews and sample collections. A semi-structured questionnaire, based on previous exposure assessments and occupational health studies from Ghana (Calys-Tagoe et al., 2015; Green et al., 2015), was used to gather information on socio-demographics and work history. A midstream urine sample (>30 mL) was collected into a plastic container at the start of each participant's visit to the clinic, typically between 10 a.m. and 4 p.m. Approximately 5 mL of blood was collected into a trace elements free BD Vacutainer tube with K₂EDTA, and placed on a blood tube roller (Microteknik) for five minutes. Urine and blood samples were stored in the refrigerator at 4–8 °C until shipment to McGill University (Montreal, Canada) where they were stored frozen (–20 °C) prior to analyses.

2.3. Elemental analysis

Blood elements analyzed included toxic chemicals (cadmium, Cd; mercury, Hg; lead, Pb) and essential elements (copper, Cu; iron, Fe; manganese, Mn; selenium, Se; zinc, Zn). Urinary elements analyzed included toxic chemicals (arsenic, As; cobalt, Co; chromium, Cr; Hg; nickel, Ni; Pb) and essential elements (Cu, Zn). Total Hg levels in blood and urine were quantified using a Direct Mercury Analyzer 80 as previously outlined (Basu et al., 2014; Rajaei et al., 2015). For all other elements, the urine and blood samples were digested with nitric acid as outlined elsewhere (Basu et al., 2011), and elemental concentrations determined using Inductively Coupled Plasma Mass Spectrometer (ICPMS; Varian 820MS).

Several analytical quality control measures were used. All laboratory glassware and plastic was acid-washed (cleaned, soaked 24 h in 20% nitric acid, and rinse 3 times in Milli-Q water) prior to use. Accuracy and precision were measured by use of certified reference standards obtained from the Institut National de Santé Publique du Québec (INSPQ; QMEQAS10U-04 urine and QMEQAS10B-09 blood). In addition, each batch run contained procedural blanks and replicate runs. For each element analyzed, the theoretical detection limit was calculated as three times the standard deviation of the mean blank value (Supplemental Table 1).

2.4. Data analyses

Preliminary data analysis included tabulation of descriptive statistics for all measurements to understand the basic features of the dataset. Results from the semi-structured questionnaire of the male workers were used to identify key job categories, and from this we were able to identify and focus upon 9 key job categories (collect, deal, sort, repair, dismantle or burn e-waste, remove wires, burn wires, smelt lead and recycle batteries). Additionally, we derived 4 main e-waste activities: dealing, sorting, dismantling, and burning e-waste materials. Blood and urine biomarkers of elemental exposures were not normally distributed. Transformations of this dataset did not achieve normality, and thus non-parametric tests were favored. For each blood and urine biomarker, estimates of central tendencies, variances, and percentiles were calculated and summarized. The primary relationships of interest were associations between elemental biomarkers with a participant's demographics and work characteristics. Comparisons with reference range values from the literature were made by calculating percentage differences and also done in a qualitative manner. Associations among elemental biomarkers and job categories and main e-waste activities were analyzed using correlational approaches (e.g., factor analyses, Spearman's). All values are reported as mean (standard deviation) or median (25th–75th interquartile range) as indicated. A p-value of 0.05 or lower was considered significant, and in some cases when performing multiple comparisons a more restrictive p-value was used and indicated. All statistical operations were performed using SPSS (v11.5, Chicago IL).

3. Results

3.1. E-waste worker demographics

The mean (SD) and median (IQR) age of the 58 male workers studied was 25.9 (7.9) and 24 (20.8–29.3), and they ranged in age from 18 to 61 (Table 1). Nearly all (96.6%) the workers were Muslim. Just over one-third (37.9%) of the participants indicated that they were single, with the rest being married (37.9% living together; 19.0% not living together), and divorced or separated (5.2%). More than half (53.4%) of the participants had no formal education and 27.6% reported having completed middle or secondary education. More than 50% of the participants had moved to the e-waste from

the North of Ghana. Most (96.6%) of the participants indicated that they slept near Agbogbloshie, 70.7% reported sleeping inside their work shed, and the mean (SD) number of years lived near Agbogbloshie was 6.0 (4.2). More than half (68.9%) of the respondents reported earning less than 20 Ghana cedis per day (~\$5USD), with 37.9% earning less than 10 cedis per day. Self-reported income was not associated (chi-squared) with recent job activities or education level.

3.2. E-waste work characteristics

All respondents worked in different aspects of e-waste at some point in their careers (Table 2). The mean (SD) and median (IQR) number of years worked in e-waste was 6.2 (4.2) and 5.0 (3.5–8.0), with a range between 6 months and 22 years. Among the 9 job categories we focused on, the average individual was active in 6.8 (2.0) categories, and this ranged from 1 to 9. Most indicated to have performed tasks in 7 job categories (31%), followed by six (17%), eight, and nine (14% each). Less than 5% of the study population indicated to performing tasks in either 1, 2, 3 or 4 job categories. The most common job category was dealing e-waste scraps (96.6% of the participants indicated to being involved) followed by dismantling (84.5%), collecting (81%), and sorting (81%) e-waste. The work data were subjected to a factor analysis to determine if job categories activities clustered in groups. The first three eigenvalues explained 58.7% of the total variance. A diagnostic assessment of the scatterplots indicated three groupings specifically, those who a) burned e-waste or wires; b) smelted lead or recycled batteries; and c) all other (n = 6) job categories.

When asked about the main activity they performed over the preceding six months, the participants could be binned into four broad e-waste activities including those who dealt e-waste materials (22.4%), sorted e-waste materials (24.1%), dismantled e-waste equipment (50%), and burned materials (3.4%).

3.3. Elemental biomarkers - descriptive summary

For every urine and blood sample studied, quantifiable results of the target elements were obtained (Supplemental Table 1). In general, the urine data was of higher quality than the blood data, though both datasets were deemed to be sufficiently high quality for analyses. The average recovery of elements from the certified reference materials was within 11% of expected value for all elements (except for blood Mn). Analytical precision was under 15% for all elements, with most being less than 5%. None of the raw elemental data were adjusted except for blood Mn and blood Pb; these were adjusted by subtracting the mean value of the procedural blanks from each sample. Blood Mn, Cd, and Pb had 11, 9 and 8 samples, respectively, that fell below the calculated theoretical detection limits, and the values obtained from the instrument were retained for analyses. Urinary elements were adjusted for specific gravity, which was normally distributed within the study population with a mean (SD) of 1.016 (0.008), and a range between 1.00 and 1.03.

Elemental analyses of the blood samples are presented for the male e-waste workers (Table 3) as well as the female service workers (Supplemental Table 2). In the absence of a suitable reference population from Ghana (or Africa), the values from the male e-waste workers were compared to numbers proposed by [Iyengar and Woittiez \(1988\)](#) as part of their effort to establish “normal values” for trace elements in biological specimens. In general, the blood elemental levels reported here are within the reference range proposed by [Iyengar and Woittiez \(1988\)](#), though in the Discussion section of this paper we expand the scope of this comparison.

Table 1

Overview of key sociodemographic measures of participants sampled from the Agbogbloshie e-waste site (Accra, Ghana) in April 2014.

	Male e-waste workers	Female service workers
# Participants	58	11
Age (years as mean, SD)	25.9 (7.9)	26.0 (12.8)
Marital Status		
Single	22 (37.9%)	3 (27.3%)
Married (living together)	22 (37.9%)	3 (27.3%)
Married (living apart)	11 (19.0%)	2 (18.2%)
Separated or Divorced	3 (5.2%)	2 (9.1%)
Widowed	0 (0%)	2 (18.2%)
Daily Income		
<GHS 10	22 (37.9%)	4 (36.4%)
GHS 11–20	18 (31.0%)	3 (27.3%)
GHS 21–30	7 (12.1%)	1 (9.1%)
GHS 31–40	4 (6.9%)	2 (18.2%)
>GHS 40	7 (12.1%)	0 (0%)
Education		
No school	31 (53.4%)	5 (45.5%)
Primary	11 (19.0%)	3 (27.3%)
Middle/JSS	12 (20.7%)	2 (18.2%)
Secondary/SSS	4 (6.9%)	1 (9.1%)

Table 2

Self-reported history of e-waste job categories amongst the 58 male workers sampled from the Agbogbloshie e-waste site (Accra, Ghana) in April 2014.

Task	n	%	Mean (SD) years performing task	Range of time performing task	Performed task during past six months
Collect E-Waste	47	81	5.4 (4.0)	2 mths–20 yrs	92%
Deal E-Waste	57	98	6.0 (4.3)	1 mth–2 yrs	100%
Sort E-Waste	48	83	6.5 (7.6)	2 mths–50 yrs	100%
Dismantle E-Waste	50	86	5.9 (4.5)	6 mths–22 yrs	98%
Repair E-Waste	18	31	5.3 (3.1)	1 mth–12 yrs	100%
Remove Wires	44	76	5.9 (4.6)	1 mth–22 yrs	98%
Burn Wires	32	55	5.8 (3.2)	2 mths–14 yrs	100%
Burn E-Waste	43	74	5.4 (3.2)	2 mths–14 yrs	93%
Smelt Lead Batteries	25	43	5.4 (3.4)	1 yr–12 yrs	83%

Table 3Description of blood and urinary elements ($\mu\text{g/L}$) for the study population of 58 male e-waste workers sampled from the Agbogbloshie e-waste site (Accra, Ghana) in April 2014. Shaded cells refer to toxic elements and un-shaded cells refer to essential elements.

		Mean	Standard deviation	Percentiles				
				10%	25%	50%	75%	90%
Blood Elements	Cd	1.7	3.0	0.2	0.5	1.2	1.6	3.1
	Hg	1.8	1.4	0.5	0.7	0.9	1.3	2.4
	Pb	79.3	58.0	26.3	40.1	63.5	99.8	142.2
	Cu	1063	723	713	762	841	925	1047
	Fe	442,757	60,229	301,222	378,254	409,666	444,298	478,246
	Mn	9.8	4.3	4.2	4.9	7.0	8.8	11.5
	Se	164	49	99	116	132	152	190
	Zn	5574	1964	3314	3954	4645	5281	5837
	As	77.5	124.0	13.3	22.6	38.3	86.6	200.2
Urinary Elements	Co	1.7	2.1	0.2	0.4	0.9	1.8	4.5
	Cr	0.9	0.5	0.2	0.5	0.9	1.2	1.5
	Hg	0.2	0.2	0.1	0.1	0.2	0.2	0.5
	Ni	15.9	16.7	6.6	9.1	12.1	17.9	22.7
	Pb	9.0	8.0	3.5	4.9	7.0	9.7	14.0
	Cu	23.8	11.9	11.2	13.4	22.1	31.3	42.5
	Zn	659	425	201	380	511	912	1316

For urine samples, elemental analyses are presented for the male e-waste workers (Table 3) as well as the female service workers (Supplemental Table 2). Urinary data were compared to the study by Asante et al. (2012) that previously measured several urinary elements in 20 male Agbogbloshie e-waste workers sampled in August 2008. There were 7 urinary elements common between our studies, and of these the mean values reported by Asante et al. (2012) for As, Co, and Hg were within the interquartile range we report here. For the other elements (Cr, Pb, Cu, Zn), our values differ from those reported by Asante et al. (2012). Notably, for urinary Cr and Cu, the mean level reported by Asante et al. is 10.5- and 7-times higher, respectively, than what we report here. To be consistent with our approach for the blood data, we also compared the urinary elements with the reference ranges provided by Iyengar et al. (1988). In doing so, the median urinary element values from our study are approximately two-fold (or greater) higher than the median reported by Iyengar and Woittiez (1988) for urinary As, Cr, Ni and Zn.

3.4. Elemental biomarkers - correlations

To explore associations among the urinary and blood elements, Spearman correlations were calculated (Supplemental Table 3). Owing to multiple comparisons, a more restrictive p-value (<0.01) was applied. There were more statistically significant correlations found between urinary elements (18/28 possible binary combinations were significant) versus those measured in blood (5/28 possible binary combinations were significant).

The blood and urine elemental data were next subjected to a factor analysis to determine whether the measured elements

clustered into particular groups. For blood elements the KMO was borderline (0.49 vs. the 0.50 rule of thumb) but deemed acceptable as we viewed this analysis to be exploratory and are cognizant of some of the datasets limitations (e.g., sample size). The first eigenvalue estimated from the matrix accounted for 24.5% of the total variance and three eigenvalues explained 60.0% of the total variance. A diagnostic assessment of the scatterplots indicated three groupings of blood elements: a) Cu and Pb; b) Se, Hg, and Fe; and c) all other elements. For urinary elements, the KMO was 0.74. The first eigenvalue estimated from the matrix accounted for 40.0% of the total variance and three eigenvalues explained 66.7% of the total variance. A diagnostic assessment of the scatterplot indicated three groupings of urinary elements: a) Zn, Cr, Pb, Co, Cu; b) Hg, Ni; and c) As.

3.5. Elemental biomarkers - comparison with demographics and work activities

When the elemental biomarker data were correlated with key demographic variables, some significant associations were found. Age correlated with blood Cd and Se, as well as with urinary Ni, Zn, and As. The number of years working in e-waste correlated with blood Cu, Zn, Cd, Se, and Hg, as well as with urinary Ni and Pb. There was no association between blood or urinary elements and participant's income or education level (except urinary Ni which was highest amongst those with secondary education).

The elemental biomarker data were evaluated by self-reported job categories. In the first analysis, the number of job categories a person reported to be actively involved with was related to the elemental biomarker values, and no significant correlations were

found. Second, the elemental biomarker values were compared between individuals indicating “Yes” to currently performing a task versus those indicating “No” with some significant differences. Notably, those who sorted e-waste had blood Pb levels that were significantly higher (2.2-fold) than those who did not, and those who performed burning activities had urinary Cu and Zn values that were 1.7-fold higher than those who did not. Third, elemental biomarker values were compared against the main job activity participants reported being involved with over the preceding six months (Fig. 1). No significant differences were found, but the two workers who selected “burning electronic waste” had amongst the highest levels of most elemental biomarkers. Those who indicated to “sorting e-waste” as their main activity had amongst the lowest exposures to all elements.

3.6. Female participants

There were 11 females recruited into an exploratory study to increase understanding of their situation as workers at Agbogbloshie who service the site. None of these women performed any tasks directly related to e-waste recycling, rather they were all involved in selling items including food and drinks ($n = 7$) and/or cigarettes ($n = 3$). There was no age difference between males and females, with females being 26.0 (12.8) years and ranging in age from 18 to 43 (Table 1). The marital status of the women interviewed was similar to that of the males with 27.3% being single and 45.5% being married. The education of the women was similar to that of the men with nearly half of the women (45.5%) having no formal education. Like the males, more than 50% of the female participants had moved from the North of Ghana. Most (81.8%) of the females participants slept near Agbogbloshie, 45.6% slept inside a kiosk shop, and the mean (SD) number of years lived near Agbogbloshie was 1.8 (1.6) and ranged from 1 month to 5 years.

Although limited, differences in elemental biomarkers were noted between the female service workers (Supplemental Table 2) and male e-waste workers (Table 3). Compared to the males, the median values were higher in females for several of the studied elements (blood Cd, Hg, Cu, Mn, Se; urinary As, Co, Cr, Hg, Ni, Pb, Cu, Zn) with urinary Ni and Zn being significantly higher amongst the females. The mean blood Pb value in males was more than double that in females. There was no difference in mean urinary specific

gravity between males (1.016) and females (1.018).

4. Discussion

There is global interest to develop and deliver interventions intended to prevent harmful exposures at e-waste sites (Heacock et al., 2016). While there is a growing body of evidence suggesting environmental and occupational health risks associated with e-waste recycling, the evidence base is relatively sparse and more studies are needed to establish a robust foundation from which actions can be properly taken. In addition, it is important to acknowledge the large variability that exists across e-waste sites. Each e-waste site, and its surrounding community, has unique socio-economic, occupational, and environmental characteristics, and as such responses and interventions are likely to be site/context-specific. Though Agbogbloshie is one of the best-studied e-waste sites worldwide with more than 30 published papers (Amoyaw-Osei et al., 2011) covering a range of disciplines (social, environmental, human health), outstanding data gaps still remain including a more detailed study of elemental exposures among area workers and residents. Some of these are addressed in the current paper.

Elemental exposures by e-waste workers have been reported in studies from China (Song and Li, 2014), but to our knowledge little is known about such exposures at sites located in other low- and middle-income countries including the Agbogbloshie site. While there are reasons to believe that workers at Agbogbloshie are being exposed to elevated levels of several toxic elements (i.e., studies documenting high levels in the water, soil, and sediment; Otsuka et al., 2012; Atiemo et al., 2012; Brigden et al., 2008; Chama et al., 2014; Asante et al., 2012; Itai et al., 2014) there is little empirical evidence of this. The study by Asante et al. (2012) on 20 male workers at Agbogbloshie established that toxic metal exposures occur, though this work was limited by a relatively low sample size, a single biomarker studied, and lack of key socio-demographic and occupational characteristics. Here we build upon the work by Asante et al. (2012) as well as previous studies by our team at Agbogbloshie (Wittsiepe et al., 2015; Feldt et al., 2014; Akormedi et al., 2013; Asampong et al., 2015; Burns et al., 2016), and capitalize upon our growing collaborative relationship with the Greater Accra Scrap Dealers Association. The socio-demographic

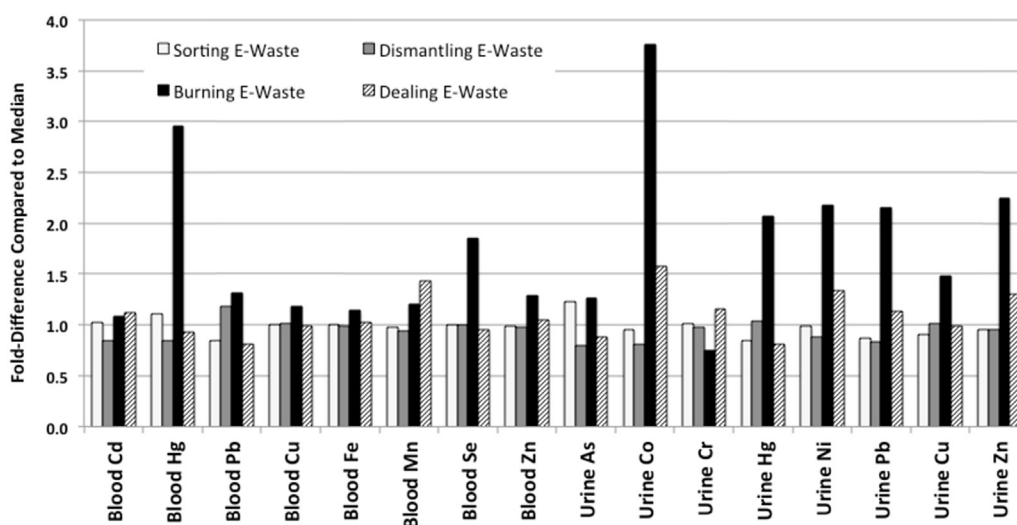


Fig. 1. Blood and urinary elements for the study population of 58 male e-waste workers sampled from the Agbogbloshie e-waste site (Accra, Ghana) in April 2014. The values are stratified according to an individual's primary self-reported job category, and compared to the population median.

characteristics of the study population here is similar to previous studies at Agbogbloshie by our research team and others thus enabling comparisons to be made.

As with other informal sector activities in West Africa, the conditions surrounding e-waste recycling at Agbogbloshie are characterized as having unsafe working conditions, poor health standards, and pervasive environmental and occupational hazards (Basu et al., 2016). Most workers live at Agbogbloshie resulting in continual exposure to hazards, and the region and its workers lack basic health and welfare services (Asampong et al., 2015). Despite such concerns, there has been little investigation of the job activities performed at Agbogbloshie. The semi-structured questionnaire we utilized revealed that e-waste workers are involved in a number of different tasks at the site, but also that many are involved with off-site activities. In addition, Agbogbloshie has a long history of being a scrap metal recycling site (Amoyaw-Osei et al., 2011) and we are not easily able to distinguish between those who recycle metals (and other items) versus those who recycle e-waste. Such variation proves challenging when trying to make workplace classifications, and to ultimately tease apart occupational activities and exposures with adverse health outcomes. In our careful review of the questionnaires, we were able to categorize the workers into 9 specific job categories but drew this from a larger list of approximately 21 self-reported activities. For data management purposes and based on the results of our factor analyses, we could further separate the group into those who “handle” e-waste (collect, deal, sort, repair, dismantle e-waste and remove wires), burn e-waste and wires, and smelt lead and recycle batteries. This type of information can be used in future research activities to design better surveys to understand workplace activities and how these relate to issues of concern such as injuries and respiratory symptoms (Asampong et al., 2015).

The current study aimed to characterize elemental exposures by focusing on both blood and urine, as well as several essential and toxic elements. Many of the elements we studied have been previously measured in the Agbogbloshie ecosystem (Otsuka et al., 2012; Atiemo et al., 2012; Brigden et al., 2008; Chama et al., 2014; Asante et al., 2012; Itai et al., 2014). We are not aware of a dataset that provides reference range values of these studied elements from the ‘typical’ Ghanaian (or African) population. In the absence of a suitable reference population from Ghana (or Africa), the values were initially compared to numbers proposed by Iyengar and Woittiez (1988) as part of their effort to establish “normal values” for trace elements in biological specimens. In general, the blood element levels reported here are within the reference range proposed by Iyengar and Woittiez (1988). This includes several essential elements including blood Cu, Fe, Mn, Se, and Zn, thus indicating a relatively healthy population. The results can also be compared to levels reported from national biomonitoring programs elsewhere. Despite being within a “normal range” according to Iyengar and Woittiez (1988), the blood Cd and Pb levels were elevated compared to background populations in the U.S. and Germany. For example, the median value reported here for Cd and Pb were 5.1 and 5.0-fold higher, respectively, than corresponding median values from males sampled during the 2009–2010 cycle of the U.S. National Health and Nutrition Examination Survey (NHANES). For blood Cd, 32.8% and 63.8% of our samples, respectively, exceeded the 95th value of aforementioned U.S. NHANES study (1.45 µg/L) and the German Biomonitoring program's reference value (1.0 µg/L). For blood Pb, 79.3% and 34.5% of our samples, respectively exceeded the 95th percentile value of aforementioned U.S. NHANES study (38.4 µg/L) and the German Biomonitoring program's reference value (90 µg/L). Further, 67.2% of those sampled exceeded the recently updated US CDC/NIOSH blood Pb guideline of 5 µg/dL (or 50 µg/L). Both Pb and Cd have been detected

at elevated levels in the region's dust (Atiemo et al., 2012), sediment (Chama et al., 2014), and soil/ash (Otsuka et al., 2012), all of which are likely exposure sources.

Urinary data from the current work was compared to the study by Asante et al. (2012) who previously measured several urinary elements in 20 male Agbogbloshie e-waste workers sampled in August 2008. There were 7 urinary elements common between our studies, and of these the mean values reported by Asante et al. (2012) for As, Co, and Hg were within the interquartile range we report here. Notably, for urinary Cr and Cu, the mean level reported by Asante et al. was 10.5- and 7-times higher than what we report here with the maximum reported levels of urinary Cu (490 µg/L) and Cr (29 µg/L) being substantially higher. The reasons for these higher exposures are not clear. Like our study, Asante et al. (2012) included several analytical quality control measures though did not normalize their urinary values with specific gravity, which could introduce some differences. To be consistent with our approach for the blood data, we also compared the urinary elements with the reference ranges provided by Iyengar et al. (1988) which showed that the median results of our study are approximately two-fold (or greater) higher than reference values for urinary As, Cr, Ni, and Zn. For urinary As we note that 39% of the participants had levels exceeding 100 µg/L, a value reported by the U.S. Agency for Toxic Substances and Disease Registry (ATSDR, 2007) to be of possible health concern.

To understand elemental exposures in the context of e-waste activities, we related the self-reported workplace activities with the blood and urine elemental data. As mentioned earlier there were challenges with the job classifications from which we had to work with, and most indicated to have performed several e-waste related tasks (e.g., 31% of the population self-reported routine involvement in seven tasks). Most interesting, those who performed burning activities had higher levels of most blood and urinary elements than those who did not. The main purpose of burning plastic off of wires is to recover copper, and the process can also liberate a range of other elements and result in direct exposures.

Besides e-waste workers (who are largely middle-aged men), the Agbogbloshie region is home to tens of thousands of people including an estimated 4500–6500 individual who work at the e-waste site (Prakash et al., 2010). Some of these workers are females who serve the site by selling water and food. The residential community that houses Agbogbloshie workers and their families (as well as others from the general population) is located east of the e-waste recycling site, about 100 m across the Odaw River. These populations are continuously exposed to many of the same hazards as the e-waste workers, including exposure to toxic elements. In our exploratory study of 11 female service workers we note that the median values of several elements studied here were higher than in the males. More study is needed of these female workers, as well as members from the at-large community (including children) to characterize their exposures to e-waste hazards.

The current study has several strengths, notably the use of two biomarkers of elemental exposures and the use of surveys that capture a range of pertinent socio-demographic and occupational variables. Further, the work is situated in a well-studied e-waste site and thus able to contribute to a growing body of work at Agbogbloshie. Nonetheless there are important limitations of our study that warrant mention. The results are subject to selection bias as the subjects self-selected themselves to participate. The study's sample size is amongst the largest of its kind but only captures 1–1.5% of the estimated workforce at the site. The study is one of the first to better characterize e-waste job categories but is challenged in the tremendous variability of specific activities with which workers are involved. An ultimate goal of this study is to increase understanding of elemental exposures for e-waste

workers, and while the current study sets a number of foundations more work is needed to couple such biomarker studies with more detailed investigations of occupational activities as well as with ecological measures to better characterize source-exposure-biomarker relationships, and to expand focus on the larger Agbogbloshie community that includes women and children.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.chemosphere.2016.08.089>

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