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HBM4EU e-waste study – Occupational exposure assessment to chromium, cadmium, mercury and lead during e-waste recycling

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ABSTRACT

Processing of electronic waste (e-waste) causes the release of toxic substances which may lead to occupational exposure.

The study aimed to gather information on potential occupational exposure during e-waste recycling, with a focus on biomonitoring of chromium, cadmium, mercury and lead.

In eight European countries, 195 workers involved in the recycling of lead batteries, white goods, brown goods and metals and plastics were studied. These workers were compared to 73 controls with no direct involvement of e-waste recycling or other metal processing activities. The samples collected consisted of urine, blood and hair samples, along with personal air samples, hand wipes, settled dust samples and contextual information. Chromium, cadmium, mercury and lead was measured in urine, hair, air samples, hand wipes and settled dust; cadmium and lead in whole blood and chromium in red blood cells.

Results showed that lead exposure is of concern, with workers from all five types of e-waste showing exposure, with elevated measurements in all matrices. Internal exposure markers were positively correlated with markers of external exposure, indicating workers are not adequately protected. Exposure to mercury and cadmium was also observed but to a much lesser extent with raised cadmium concentrations in urine and blood of all workers when compared to controls and raised mercury concentrations were found in brown goods workers when compared to controls.

This study has highlighted exposure concerns when processing e-waste, particularly for lead across all waste categories studied, indicating a need for improved control measures in this sector.

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1. Introduction

The Human Biomonitoring for Europe (HBM4EU) initiative aimed to harmonise human biomonitoring (HBM) methodologies to facilitate its use in the assessment of exposure and health risk assessment for chemicals in the environment, in the workplace, or in consumer products (Ganzleben et al., 2017). One of the occupational exposure surveys performed as part of HBM4EU was focussed on investigating workers' exposure to hazardous chemicals in electronic waste processing/recycling industries (Ganzleben et al., 2017; Scheepers et al., 2021). The amount of waste from electrical and electronic equipment (known as WEEE or e-waste) is increasing rapidly year on year and has been termed the fastest growing stream of waste European Commission (2023a). This is in part as a result of the Circular Economy Action Plan European Commission (2023b), for example, it is predicted that the volume of e-waste will double in the next 15 years from the 53.6 million tonnes discarded globally in 2019 (Bruun and Lein, 2021). In 2002, the WEEE Directive 2012/19/EU (EUR-LEX, 2012) together with The Restriction of Hazardous Substances (RoHS) Directive 2011/65/EU (EUR-LEX, 2011) were developed and brought into European Law. The main objectives of the WEEE Directive are to prevent the creation of WEEE, to contribute to the efficient use of resources through re-use, recycling and recovery and to improve environmental performance in the life cycle of WEEE. The RoHS Directive restricts the use (with some exceptions) of 10 hazardous materials in the manufacture of electronic and electrical equipment (EEE), including hexavalent chromium (Cr(VI)), cadmium, mercury and lead.

The processing or recycling of e-waste can lead to the possibility of occupational exposure to many different chemical elements and organic compounds. In this study we have been especially interested in chromium, cadmium, mercury and lead, which are not only the chemical elements with restricted use as defined by the RoHS Directive but were also separately identified as priority substances by the HBM4EU programme HBM4EU – Human Biomonitoring for Europe. There is a vast array of health effects associated with these four elements, especially lead. Evidence has shown lead exposure even at low levels (less than 50 μg/L and less than 100 μg/L) can have non-cancer related detrimental effects (ATSDR, 2020; NTP – National Toxicology Program, 2012). In addition, The European Chemical's Agency (ECHA) Risk Assessment Committee (RAC) has raised the possibility of lead being a carcinogen to humans at high exposure levels in their occupational exposure limits (OELs) recommendation report (ECHA – European Chemicals Agency, 2020). ECHA also reports recent or upcoming reductions for binding OELs, not just for lead but also Cr(VI) and cadmium along with Biological Limit Value (BLV) reductions suggested for cadmium and lead (ECHA – European Chemicals Agency, 2020; ECHA – European Chemicals Agency, 2021), emphasising the need for current investigations into the occupational exposure of these chemical elements.

There is limited data for the occupational exposure to chemicals during e-waste recycling (Arain and Neitzel, 2019), with only three European studies using human biomonitoring to assess the internal exposure in e-waste recycling industries (Julander et al., 2014; Gerding et al., 2021; Hanser et al., 2022). Suitable methods for exposure assessment can support sound occupational practices and risk management measures in e-waste processing, reducing workers exposure.

The study reported here was part of a multi-centre HBM4EU e-waste study involving institutes from Belgium, Finland, Latvia, Luxembourg, the Netherlands, Poland, Portugal and the United Kingdom (UK). The study explored occupational exposure to chromium, cadmium, mercury, lead, phthalates, non-phthalates plasticisers, brominated flame retardants, organophosphate flame retardants and polychlorinated biphenyls to determine if current health, safety and control practices in place across Europe are sufficient in protecting workers. The goal was to generate new data from both external (for example, air measurements) and internal exposures (for example, biological samples) of workers processing and recycling e-waste understand potential exposure hazards and promote good working practices to help reduce the risk of exposure to workers. It is hoped that by developing sustainable practices and methods of exposure assessment we can ensure that the processing and recycling of e-waste is achievable whilst also protecting workers as recycling activities and companies dedicated to these processes increase across Europe.

As a result, new data has already been generated by investigating different biological matrices, to compare levels of phthalates and cyclohexane-1,2-dicarboxylic di-isononyl ester (DINCH) (Cleys et al., 2024) and polychlorobiphenyls persistent organic pollutants (Cseresznye et al., 2024) in the occupationally exposed workers with a non-occupationally exposed control group. Follow-up publications (in preparation) will describe other datasets such as organophosphate flame retardants and the applicability and relevance of different biomarkers of effect. This paper describes in detail the chromium, cadmium, mercury and lead results of the HBM4EU e-waste study.

2. Method & materials

To enable a standardised approach, standard operating procedures (SOPs) were developed on the collection, handling, storage and transfer of both biological and occupational hygiene samples, harmonised comparable samples and data were collected from each participating country. We refer to Scheepers et al. (2021) for the HBM4EU e-waste study protocol, describing company recruitment, the collection of urine, blood and hair samples. In addition to, personal inhalable and respirable air samples, hand wipes and settled dust and, to help understand the contribution of each route of exposure and the concentration of potential chemicals in the workplace, a worker and workplace contextual information was also collected. Therefore, only brief details of samples collected, and analytical methods applied are provided in this paper.

Inhalable air samples refer to the fraction of airborne material that enters the nose and mouth during breathing, whilst respirable refers to the inhaled airborne fraction that penetrates to the lower gas exchange regions of the lung (HSE – Health and Safety Executive, 2014).

Urine samples and hair samples were collected for the analysis of chromium, cadmium, mercury and lead. Venous blood samples were collected for the analysis of cadmium and lead in whole blood and chromium in red blood cells (RBC).

Chromium was not measured in whole blood due to not being able to distinguish between hexavalent (CrVI) and trivalent (CrIII) chromium, whereas RBCs reflects exposure specifically to CrVI (Scheepers et al., 2021). Mercury was not measured in whole blood as it reflects both occupational exposure to inorganic mercury compounds and dietary exposure to organic mercury compounds through the consumption of seafood, whereas urine mostly only reflects inorganic mercury exposure (Scheepers et al., 2021).

Both inhalable and respirable personal dust measurements, hand wipes and settled dust samples were collected for the analysis of chromium, cadmium, mercury and lead. The sample type and the number of workers which samples were collected from by each country are outlined in Table 1.

Workplace site visits were conducted by a research team from each participating country. Study protocols have been approved by ethical review boards in each of the participating countries. For details see the Ethics section at the end of this manuscript.

Analyses of exposure markers were performed by laboratories experienced in the analysis of a specific metal (chromium, cadmium, mercury and lead). The analytical details of the quality control information for the laboratories analysing samples can be found in Supplementary Table S1. Supplementary Table S2 presents an overview of the analytical limits of quantification (LOQs) for all analysis and sample transfers between partners and laboratories.

Table 1
The number and type of sample collected from e-waste workers (and control workers) by each country.

	Number of exposed workers and (controls) sampled					
	Urine	Blood	RBC	Hair	Air	Wipes
Belgium	41 (10)	41 (10)	41 (10)	7 (0)	14	14
Finland	16 (7)	16 (7)	–	–	13	12
Latvia	13 (6)	13 (6)	–	11 (4)	13	0
Luxembourg	10 (14)	6 (10)	6 (10)	3 (11)	9	9
The Netherlands	28 (19)	26 (19)	26 (19)	6 (12)	27	0
Poland	15 (5)	15 (5)	–	–	0	0
Portugal	30 (12)	29 (12)	29 (12)	27 (0)	17	0
UK	42 (0)	42 (0)	–	–	41	42

- Country did not collect this type of sample matrix. (0) controls for this matrix were not collected.

2.1. Study population

Exposed workers were recruited in four types of recycling of e-waste with the potential for exposure to chromium, cadmium, mercury and lead: sorting, dismantling, shredding and pre-processing. Samples were collected from exposed workers over the age of 18 years. Samples were collected from the occupationally exposed workers both pre-shift at the beginning and post-shift toward the end of the worker's shift cycle (typically on the 3rd to 5th consecutive working day, depending on the schedule). E-waste workers followed varying shift patterns, including night shifts, weekend work, and 8–12-hr days, so 'working week' refers to their individual work routine rather than a standard Monday-Friday schedule.

Samples were also collected from workers who were not occupationally exposed to chromium, cadmium, mercury and lead through e-waste recycling, to form a comparison control group, also >18 years. The control group consisted of workers from two categories: those who worked within the same company as the occupationally exposed but were not involved with e-waste recycling (Within Company controls) and those who worked in companies or industries separate from e-waste or metal processing industries (Outwith company controls). This approach was used, because in the HBM4EU Chromates Study, Within company controls were identified to have bystander exposure (Santonen et al., 2022).

2.2. Blood and urine sample collection and analysis

One venous blood sample was collected using a single-use syringe from the occupationally exposed workers towards the end of the working week and for the control group workers at any time during the working week. For metal biomarker measurement, the blood sample was transferred to two blood tubes. One blood tube was used for the analysis of cadmium and lead in whole blood and one for the analysis of chromium in RBC. To analyse chromium in RBC, separation of blood fractions was conducted at the local laboratory according to Devoy et al. (2016) within 8 h from the original blood collection. RBC chromium results were corrected for haematocrit 2-value (HT2) which is measured after 3 washing steps.

For the occupationally exposed workers, two spot urine samples were collected: a pre-shift sample at the start of the working week, and a post-shift sample at the end of shift towards the end of the working week. One spot urine sample was collected from the control group workers at any time during the working week. Urinary metal results were also adjusted for urinary creatinine.

Inductively coupled plasma – mass spectrometry (ICP-MS) was used to quantify total chromium, cadmium, mercury and lead in urine samples and cadmium and lead in whole blood, except the analysing laboratory in Portugal and Latvia that used graphite furnace – atomic absorption spectrometry (GFAAS) to quantify elements in blood samples and chromium in RBC (please see Supplementary Table S1).

2.3. Hair sample collection and analysis

Hair samples were collected before the work shift at the beginning of the working week. At least 500 mg of hair was collected by cutting as close to the scalp as possible using scissors (full titanium or undamaged titanium-coated blades). Precaution procedures, such as wearing gloves, disinfection of scissors, type of scissors and using cardboard sheets to transport samples, were in place to avoid external contamination of the hair samples. Hair samples were prepared according to Duca et al. (2014), a summary of the analytical procedure including quality control information can be found in Supplementary Table S3.

2.4. Air and dermal wipe sample collection and analysis

Personal air and dermal hand wipe samples were collected on the post-shift sampling site visit. These samples were only collected from the occupationally exposed workers.

Personal inhalable and respirable dust were simultaneously sampled in the breathing zone of the worker and collected using an Institute of Occupational Medicine (IOM) sampler (flow rate 2 L/min) and a Higgins Dewel cyclone (flow rate 2.2 L/min) respectively. The sampling cassettes were loaded with 25 mm mixed cellulose ester filters.

Wipe samples were collected at the following time points: pre-shift, breaks, lunch and post shift. A single wipe was collected from the dominant hand using SKC Ghost Wipes. A separate wipe was used for each repeat sampling throughout the shift. The number of samples collected per worker was dependent on the duration of the work-shift and the number of breaks. A standardised wiping procedure of both the front and back of the hand was applied (Scheepers et al., 2021).

The analytical details for air and wipe sample analysis shown in Supplementary Table S1 following either OSHA Method ID-125G (OSHA – Occupational Safety and Health Administration, 2002), NIOSH Method 7302 (NIOSH, 2014) and/or NIOSH Method 9102 (NIOSH, 2003) with modifications (Supplementary Table S4). Validated QA/QC procedures to ensure data comparability are presented in Table S1.

Air samples were collected for a representative period of the work shift and the results are expressed as an 8-h time weighted average (8-h TWA). For hand wipes, average hand areas of 445 cm^2 per female hand and 535 cm^2 per male hand were used to express the results per cm^2 hand area (EPA – Environmental Protection Agency, 2011).

2.5. Settled dust sample collection and analysis

Settled dust samples were collected using a vacuum cleaner (Museum Vac®) loaded with pre-weighed filter bags. However, Portugal used a different collection method, namely a shovel, due to the damp state of the settled dust that did not allow a vacuum procedure. Settled dust samples were collected near the end of the work shift at locations where participating workers performed most of their tasks. For each similar exposure group identified in a company, one settled dust sample was collected from one square metre of area at the worksite. Settled dust samples were collected in 11 out of 16 participating companies. The number of samples collected varied from 1 to 9 per company. One field blank per company was also collected, with the Ziploc freezer bag used to store and transport the pre-weighed filter bags remaining sealed (Scheepers et al., 2021).

2.6. Questionnaires

Contextual information was collected by two questionnaires. The first questionnaire was completed by the company representative before the sampling campaign started. The company information collected covered the workplace operating conditions, previous occupational health surveillance and the cleaning and hygiene facilities. The second questionnaire was completed by the worker and was interview-led by a member of the research team. This was completed on the post-shift sampling day and collected information such as job activities, workplace tasks performed that day, personal protective equipment (PPE)/respiratory protective equipment (RPE) and engineering controls used and personal contributions to potential elevated internal doses of chromium, cadmium, mercury or lead (e.g., smoking and dietary habits, implants, and hobbies).

2.7. *Statistical analysis*

Statistical analysis was performed using R (version 4.4.0) and RStudio (version 2023.03.1). Shapiro-Wilk tests were used to assess normality. As the data was skewed (as expected), non-parametric tests were used in the form of paired and unpaired tests such as Wilcoxon and Mann-Whitney U tests (2-tailed); p-values of <0.05 were considered statistically significant. Comparisons and correlations were performed using Spearman Correlation; where results less than the limit of quantification (LOQ) comprised more than 50 % of the dataset for the occupationally exposed workers, statistical comparisons and correlations were not performed. Descriptive statistics including mean, median, range and percentile of concentrations were calculated using Microsoft Excel 2016 and graphs and plots were prepared using GraphPad Prism 9 version 4.1 (GraphPad Software, USA). Values below the LOQ were substituted by LOQ/2 during the statistical processing (Hornung and Reed, 1990). Only results for exposure groups with more than 10 samples are presented. To interpret the size of a correlation with the Spearman Correlation coefficient (r_s), the following thumb rule was used (Chan, 2003).

- Weak correlation: $0 < |r_s| \leq 0.2$
- Fair correlation: $0.2 < |r_s| \leq 0.5$
- Moderate correlation: $0.5 < |r_s| \leq 0.7$
- Strong correlation: $0.7 < |r_s| \leq 1$

3. Results

A total of 268 workers participated in this study, consisting of 195 exposed workers and 73 unexposed workers (control group). Table 2 shows the characteristics of the participants. The exposed workers were predominantly males (88 %) whilst the control group were approximately two thirds' males 63 %. The mean age of the exposed workers and controls was similar at 42 yrs and 40 yrs, respectively. Cigarette smokers accounted for 39 % of the exposed workers, and 18 % of the control group.

The original worker categories were based on the four activities of e-waste processing as targeted through recruitment: (i) sorting, (iii) dismantling, (iii) shredding and pre-processing and (iv) metal processing. However, to enable the data to be more comparable the workers were split into five distinct categories of e-waste. This was based on the knowledge available on the type of waste handled by workers.

1. Lead battery workers
2. White goods workers (domestic appliances I.e., refrigerators and freezers, washing machines and dryers).
3. Brown goods workers (electronic appliances I.e., televisions, radios, computers, DVD players, lighting and bulbs).
4. Metals and plastics workers (The occupation of these workers was classified as dismantler, sorter, grinder, mixer, machine driver, process worker or production line manager at workplaces where metals and plastics were recycled).
5. Miscellaneous workers (all other workers for example, team leaders, managers, and forklift truck drivers). Supplementary Table S5 lists all workers classed as miscellaneous.

Table 3 outlines the number and different types of sample matrix collected for each of the five types of e-waste in addition to the number and type of sample matrix collected from the control group. The variety of biological samples and e-waste categories recruited varies across each country as shown in Tables 1 and 3 Workers recycling brown goods were recruited the most ($n = 81$ workers), with white goods the second most recruited type of e-waste ($n = 46$ workers).

3.1. *Control group workers*

Table 4 shows the median and 95th percentile (P95) of the control group urine samples in μg/g creatinine for total chromium, cadmium, mercury and lead, in addition to the median and P95 for whole blood samples (cadmium and lead) and RBC-chromium HT2-corrected and published background population data from the UK (Morton et al., 2014), Germany (Heitland and Köster, 2021), Belgium (Hoet et al., 2013, 2021) and France (Frery et al., 2011; Oleko et al., 2024) for comparison where available in addition to RBC chromium unexposed control group mean and P95 from Santonen et al. (2022). All results compared well to previously published background population data and Mann-Whitney statistical analyses showed there were no statistical differences between the Within and Outwith Company control groups urinary or blood results. Therefore, the control group was treated as one and not subdivided, results are referred to as All-controls. One individual in the All-Control group had an elevated urinary chromium results of 8.5 μg/g creatinine (the next closest result being 1.38 μg/g creatinine). The worker questionnaire of contextual information indicated that this individual had a metal hip replacement 8 years before, most likely attributing this high value Schaffer et al. (1999). Table 4 shows the P95 values with and without this urinary chromium result; to prevent skewing of the data, from this point forward, this individual elevated chromium result was removed from the All-controls dataset.

3.2. *Worker urinary results*

Fig. 1 and Table S6 in the supplementary information shows the statistical summary in μg/g creatinine of the median, range, P95, the number of samples and percentage below the limit of quantification (LOQ) for the pre and post working week urine samples for chromium,

Table 2
Worker characteristics for the occupationally exposed workers in each recycling category and the control group.

	Number of workers	Mean age (yrs.)	Males	Females	Smokers	Former smokers	Non-smokers
All exposed workers	195	42	172 (88 %)	23 (12 %)	76 (39 %)	25 (13 %)	93 (48 %)
Lead battery workers	26	49	24 (92 %)	2 (8 %)	9 (35 %)	5 (19 %)	12 (46 %)
White goods workers	46	44	44 (96 %)	2 (4 %)	19 (41 %)	4 (9 %)	23 (50 %)
Brown goods workers	81	38	67 (83 %)	14 (17 %)	25 (31 %)[a]	11 (14 %)[a]	44 (54 %)[a]
Metals and plastics workers	21	43	19 (90 %)	2 (10 %)	10 (48 %)	2 (10 %)	9 (43 %)
Miscellaneous e-waste workers	21	41	18 (86 %)	3 (14 %)	13 (62 %)	3 (14 %)	5 (24 %)
All Controls	73	40	46 (63 %)	27 (37 %)	13 (18 %)	8 (11 %)	51 (71 %)
Within company	43	41	26 (60 %)	17 (40 %)	5 (12 %)	5 (12 %)	33 (77 %)
Outwith company	30	39	20 (67 %)	10 (33 %)	8 (28 %)[a]	3 (10 %)[a]	18 (60 %)[a]

[a] 1 individual from brown goods workers and 1 individual from the Outwith control group did not disclose their smoking status. These individuals have not been listed as a cigarette smoker, former smoker or non-smoker.

Table 3
Numbers of samples collected of each sample matrix from each worker category.

	Urine pre- shift (n)	Urine post- shift (n)	Whole Blood (n)	Cr-RBC HT2-corrected (n)	Hair (n)	Inhalable Air (n)	Respirable Air (n)	Wipe samples (n)
All exposed workers	178 (162)[a]	192	187	102	82	133	133	77
Lead battery workers	26	26	26	26	24	17	17	–
White goods workers	46	45	41	37	11	38	39	12
Brown goods workers	55	80	79	24	6	48	46	47
Metals and plastics workers	20	21	21	4	11	16	16	3
Miscellaneous e-waste workers	15	21	20	5	3	14	15	15
All Controls	73	–	69	51	27	–	–	–
Within company	43	–	43	29	14	–	–	–
Outwith company	30	–	26	12	13	–	–	–

[a] Pre-shift urine samples for 16 workers at a brown goods recycling site were not labelled. Group contained workers classed as "miscellaneous". Unable to categorise.

Table 4
The median and 95th percentile (P95) of urinary chromium, cadmium, mercury and lead in μg/g creatinine and whole blood cadmium and lead and RBC chromium haematocrit 2 corrected (HT2-corrected) for All-controls, Within company and Outwith company controls in addition to previously published background population data from the UK, Germany, Belgium and France for comparison (where available).

	Urine Chromium μg/g creatinine		Urine Cadmium μg/g creatinine		Urine Mercury μg/g creatinine		Urine Lead μg/g creatinine	
	median	P95	median	P95	median	P95	median	P95
All controls (n = 72)	0.22	0.95 **(0.77)**[a]	0.13	0.48	0.27	1.35	0.36	0.85
Within company	0.21	1.32 **(1.01)**[a]	0.13	0.61	0.22	1.29	0.40	1.78
Outwith company	0.27	0.79	0.13	0.40	0.39	3.36	0.34	0.73
Morton et al. (2014) UK (n = 132)	0.42	1.31	0.17	0.57	0.67	2.54	0.57	7.46
Heitland and Köster (2021) Germany (n = 102)	–	0.43	–	0.63	–	0.96	–	1.4
Hoet et al. (2013) Belgium (n = 1022)	0.11	0.270	0.243	0.813	0.31	1.69	1.78	2.20
Frery et al. (2011) France (n = -various)	0.17 n = 1991	0.54	0.29 n = 1930	0.91	0.56 n = 365	1.80	–	–
Oleko et al. (2024) France (n = 2419)	0.77	3.13	0.55	2.15	1.16	4.55	–	–

	Blood Cadmium μg/L		Blood Lead μg/L		RBC Chromium HT2-corrected μg/L	
	median	P95	median	P95	median	P95
All controls (n = various)	0.22 n = 69	1.15	11 n = 57	25	1.57 n = 51	8.04
Within company	0.23	0.95	12	25	1.23	5.67
Outwith company	0.20	1.86	10	**	2.57	8.74
Santonen et al. (2022) Europe (n = 175)	–	–	–	–	0.63	5.00
Heitland and Köster (2021) Germany (n = 102)	–	1.7	–	26	–	–
Frery et al. (2011) France (n = 1949)	–	–	25	73	–	–
Hoet et al. (2021) Belgium (n = 380)	0.68	1.79	11	27	–	–

[a] P95 result when the elevated urinary chromium result from one metal hip replacement control is removed from the dataset. ** Not enough samples (n < 20) to accurately calculate the 95th percentile.

cadmium, mercury and lead in the five worker categories and the All-Controls group.

3.2.1. *Chromium*

The median and P95 results for both pre and post working week urine samples for lead battery, white goods and brown goods workers are not significantly different to the All-Controls group and the previously published background reference study data reported in Table 4. This is also the case for the median results for both the metals and plastics workers and miscellaneous workers; however, the P95 values are raised due to one worker in each category having a higher urinary chromium result than the rest of the workers (with no differences in their workers questionnaire of contextual information from their co-workers to determine why). This did not impact on the statistical analysis and overall, there was not a significant difference from pre to post working week for any of the five worker categories. Indicating that worker exposure to chromium in e-waste recycling is generally low.

3.2.2. *Cadmium*

As demonstrated in Fig. 1, it is important to note that all the urinary cadmium concentrations were low, with median and P95 concentrations not being significantly different to the All-controls group and the previously published background reference study data reported in Table 4. Mann-Whitney statistical comparisons showing a significant difference between the All-controls group and the post shift urine samples for lead battery ($p = 0.003$), white goods ($p = 0.04$), brown goods ($p = 0.01$), and metals and plastics ($p = 0.04$) but not miscellaneous workers ($p = 0.52$).

3.2.3. *Mercury*

As shown in Fig. 1, the median urinary mercury concentrations for all five worker categories were not significantly different to the median concentrations reported for the All-controls group and the background population study data reported in Table 4. However, the highest urinary mercury results were found in brown goods workers with a pre to post working week P95 increase from 2.91 to 6.74 μg/g creatinine. In contrast, white goods workers had the lowest urinary mercury concentrations, with a pre to post median of 0.25–0.28 μg/g creatinine. The P95 of white goods workers is elevated by a single worker only which is not the case with the P95 from brown goods workers, where several workers had elevated results. Mann-Whitney statistical analysis indicated a statistically significant differences between the All-Controls group and both pre and post shift urine samples for lead battery ($p = 0.03$ and $p = 0.002$) and brown goods (pre and post were both $p < 0.001$) workers only. Metals and plastics workers showed a significant difference for the All-controls group when compared with the pre working week sample results ($p = 0.01$) but not post working week ($p = 0.16$). There was no significant difference between the All-Control group results compared with white goods or miscellaneous workers for pre or post working week urinary mercury results.

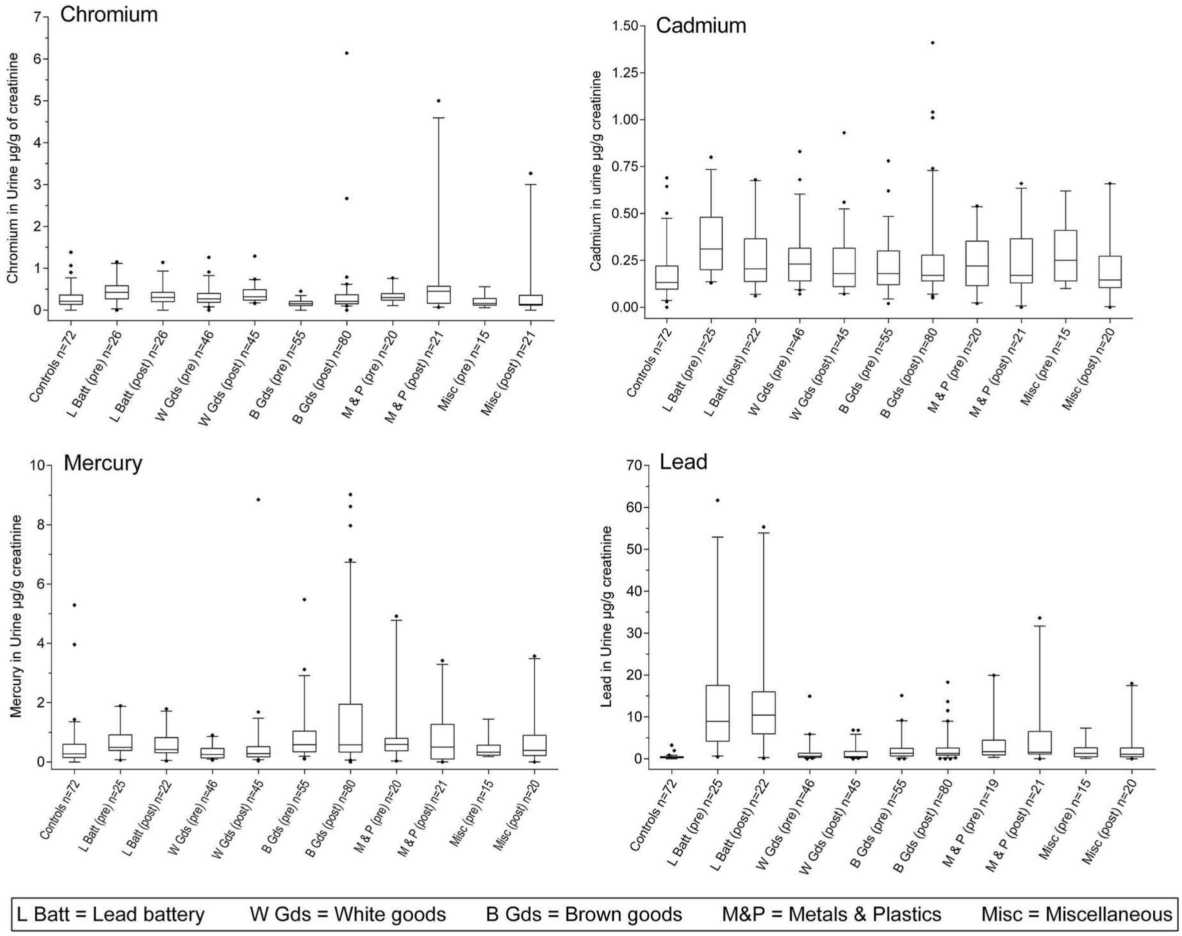


Fig. 1. Box and Whiskers plot for urinary chromium, cadmium, mercury and lead in each worker category (pre and post shift) and the All-controls group. Box plots: Bottom and top represent the 25th and 75th percentiles, whilst the horizontal line is the median. The lower and upper end of the whiskers represent the 5th and 95th percentile.

3.2.4. Lead

As shown in Fig. 1, the median and P95 were elevated for all worker categories when compared against the All-controls group. Mann-Whitney statistical comparisons confirmed this significant difference between the All-controls group and lead battery (pre and post $p < 0.001$), white goods (pre $p < 0.001$ and post $p = 0.007$), brown goods (pre and post $p < 0.001$), metals and plastics (pre and post $p < 0.001$) and miscellaneous (pre $p = 0.001$ and post $p < 0.001$) workers. Lead battery workers had the highest urinary results with both elevated median (pre 8.95 and post 10.41 µg/g creatinine) and P95 (pre 52.9 µg/g creatinine; n = 25 and post 53.9 µg/g creatinine; n = 22) results. The second highest P95 result was from the metals and plastics workers, however, unlike the lead battery workers, the metals and plastics workers median results were much lower, and comparable to the other three worker categories. The lowest urinary lead results were observed in white goods workers. However, Wilcoxon statistical analysis showed there was no statistically significant difference between the pre and post results for lead battery ($p = 0.59$), white goods ($p = 0.88$), brown goods ($p = 1.00$), metals and plastics ($p = 0.05$) or miscellaneous ($p = 0.12$) workers.

3.3. Worker blood results

Table S7 in the supplementary information shows the statistical summary in µg/L of the median, range, P95, the number of samples and percentage below the LOQ for lead and cadmium in whole blood and chromium in RBC's HT2-corrected in the five worker categories and the All-controls group.

3.3.1. Cadmium

Fig. 2 shows that the median and P95 results of each of the five worker categories was higher than the All-controls group median and P95 (except the median of lead battery workers), but the median results are not higher than those reported in the published background data detailed in Table 4. Mann-Whitney statistical comparisons showed there was a significant difference between the All-controls group and white goods ($p < 0.001$), brown goods ($p = 0.003$), metals and plastics ($p = 0.006$) and miscellaneous ($p = 0.04$) workers but not for lead battery workers ($p = 0.84$). Lead battery workers had the highest P95 and reported the highest single blood cadmium result.

3.3.2. Lead

Fig. 2 shows that all five categories of workers had elevated blood lead concentrations in comparison to the All-controls groups. Complementing this, Mann-Whitney statistical comparisons showed a strong significant difference between the All-controls group and all five categories of workers ($p < 0.001$). The highest occupational exposure to lead was found in lead battery workers with a median and P95 of 185 µg/L and 413 µg/L, respectively. The median blood lead concentrations of white goods, brown goods, metals and plastics and miscellaneous workers are 22 µg/L, 38 µg/L, 43 µg/L and 24 µg/L, respectively. In comparison, the median and P95 of the All-controls group was 11 µg/L and 25 µg/L, respectively. The white good worker category exhibited the lowest P95 of 102 µg/L, indicating all five worker categories have

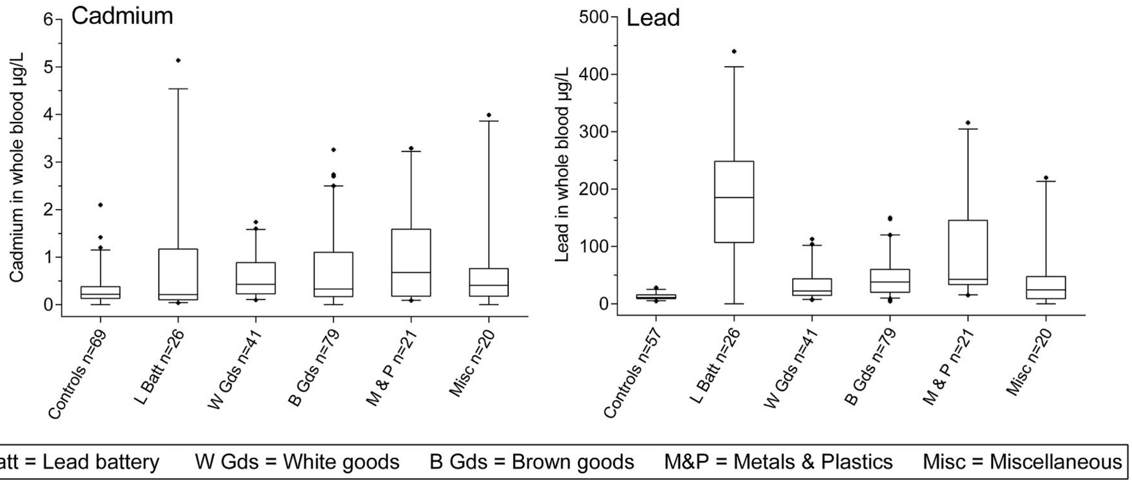


Fig. 2. Box and Whiskers plot for Cadmium and Lead in whole blood in each worker category and the All-Control group. Box plots: Bottom and top represent the 25th and 75th percentiles, whilst the horizontal line is the median. The lower and upper end of the whiskers represent the 5th and 95th percentile.

workers exhibiting occupational lead exposure.

3.3.3. *Chromium-RBC (HT2-corrected)*

The chromium in RBC HT2-corrected results showed that the median results for lead battery, brown and white goods workers were not significantly different to the All-Control group (see Supplementary Fig. S7). However, lead battery and white goods workers reported a P95 of 11.6 µg/L and 14.5 µg/L, respectively, in comparison to the 8.04 µg/L of the All-Control group. It is important to note that although 26 chromium RBC HT2-corrected results were reported for lead battery workers, 50 % were below the limit of quantitation. In addition, less than 10 sample results were reported for metals and plastics workers and miscellaneous workers. This data is not reported.

3.4. *Additional biological monitoring statistical findings*

Statistical analysis found there was a positive contribution of cadmium in both blood and urine of workers who smoked cigarettes. Table 5 shows the increasing median and P95 of non-smokers, former smokers and smokers for both blood and urinary cadmium results. Mann-Whitney analysis showed there was a strong significant difference between both smokers and non-smokers ($p < 0.001$) and smokers and non-smokers including former smokers ($p < 0.001$) for both the All-controls group and the occupationally exposed workers for cadmium in blood. In addition, there was also a strong significant difference between smokers and non-smokers (including former smokers) for both pre and post working week urine samples for the workers ($p < 0.001$), but there was no significant difference in control urinary cadmium results for smokers versus non-smokers ($p = 0.09$) and smokers versus non-smokers (including former smokers) ($p = 0.09$).

The contribution of mercury from eating seafood and fish to the urinary mercury results was also assessed by statistical analysis. Information on the frequency of fish and seafood consumption was collected via the worker questionnaire in the form of never, once or twice a week, three to four times per week or every day. However, only 3 workers consumed fish or seafood every day, 25 workers said three or four times per week, 165 workers responded once or twice per week and 31 said they never ate fish or seafood. Therefore, statistical analysis could not be accurately performed on all results. Nevertheless, a significant difference was found between those that ate seafood three or four days per week compared to never ($p = 0.036$) and three to four days per week plus every day compared to never ($p = 0.019$) in pre shift urine samples, but not in post shift urine samples.

3.5. *Hair results*

The chromium, cadmium, mercury and lead in hair results are presented in Fig. 3. However, only lead battery, white goods and metals and plastics workers results are compared against the All-Control group due to only 5 and 3 hair samples collected from brown goods and miscellaneous workers, respectively. It is also, important to note that whilst 27 and 24 hair samples were collected from the All-Control group and lead battery workers, only 11 hair samples were collected and analysed from white goods workers and metals and plastics workers therefore, comparisons should be interpreted cautiously.

The median chromium concentration in hair for all the worker categories were not significantly different to the All-Control group median of 10.3 µg/g. However, three of the five worker categories had individuals with elevated hair concentrations, for example 141 µg/g, 221 µg/g and 466 µg/g where the maximum chromium in hair concentrations measured for a lead battery, white goods and brown goods workers, respectively.

Metals and plastics workers had the highest cadmium results, followed by lead battery workers. Both showing a statistically significant

Table 5
Statistical summary of the median, 95th percentile and (number of samples) for cadmium in whole blood and urine for cigarette smokers, former smokers and non-smokers in the All-Control group, the occupationally exposed workers and all combined.

	Blood Cadmium µg/L			Urine Cadmium µg/g creatinine		
	Smoker Median, P95 (n)	Former Smoker Median, P95 (n)	Non-Smoker Median, P95 (n)	Smoker Median, P95 (n)	Former Smoker Median, P95 (n)	Non-Smoker Median, P95 (n)
All-controls	0.70, - [a] (11)	1.9, - [a] (8)	0.20, 0.73 (49)	0.20, - [a] (13)	0.14, - [a] (8)	0.12, 0.54 (50)
All exposed Workers	1.12, 3.32 (74)	0.20, -[a] (17)	0.22, 1.17 (88)	0.28, 0.65 (137)	0.17, 0.48 (32)	0.16, 0.56 (164)
All (Controls and workers)	1.0, 3.12 (85)	0.20, 2.39 (25)	0.21, 0.99 (137)	0.27, 0.63 (150)	0.16, 0.46 (40)	0.15, 0.54 (214)

[a] Not enough samples ($n < 20$) to accurately calculate the 95th percentile.

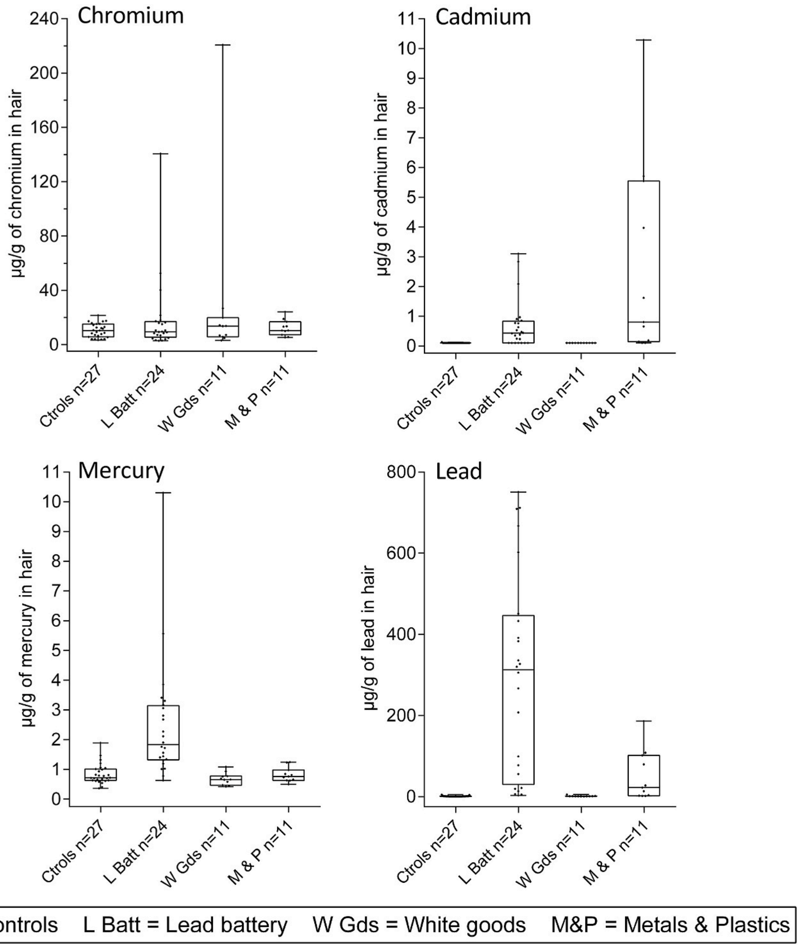


Fig. 3. Box and Whiskers plot for chromium, cadmium, mercury and lead in hair for Battery, White Goods and Metals and Plastics workers and the All-controls group. Box plots: Bottom and top represent the 25th and 75th percentiles, whilst the horizontal line is the median. The lower and upper end of the whiskers represent the minimum and maximum, the dots represent each individual result.

difference ($p < 0.001$) when compared against the All-Control group. Cadmium results for white goods and brown goods workers were less than the LOQ.

Elevated mercury hair concentrations were only seen in lead battery workers, with a statistically significant difference of $p < 0.001$ when compared against the All-Control group.

Lead battery workers showed the highest levels of lead in hair with a median of 313 µg/g (maximum concentration: 751 µg/g) in comparison to a median of 0.81 µg/g (maximum concentration: 5 µg/g) from the All-Control group. Metals and plastics workers also had an elevated median lead result of 22 µg/g (maximum concentration: 186 µg/g). Mann-Whitney statistical comparisons showed there was a significant difference between the All-controls group, and both lead battery and metals and plastics workers ($p < 0.001$) for lead in hair. White goods and brown goods workers showed no or low lead exposure.

3.6. *Industrial hygiene sampling results*

Industrial hygiene samples were only collected from the occupationally exposed workers. However, not every worker provided air and hand wipe samples, but within each similar exposure group at least one air sample and hand wipes were collected (Scheepers et al., 2021). Therefore, the number of industrial hygiene samples collected is lower than the number of biomonitoring samples collected. The results for total chromium, cadmium, mercury and lead in air samples and hand wipes are presented below. Due to the limited number of samples, the results for the settled dust samples can be found in Table S8 in the Supplementary Information.

3.6.1. *Air monitoring*

The air monitoring results for chromium, cadmium and lead in different worker groups are presented in Table 6. The mercury air monitoring results are presented in the Supplementary Table S9. Please note that the study design specified a sampling strategy which is not suitable for the collection of mercury vapours. Therefore, the mercury results for those exposed to mercury vapour represent an underestimate of exposure and should not be used to inform risk assessment. All results are represented as an 8 h time weighted average (TWA). The occupational exposure limits (OELs) stated are for inhalable air fractions only, there are no OELs specifically for respirable dust fractions.

The standout elevated air concentrations were observed for lead in lead battery workers. Median concentrations of inhalable lead in lead battery workers were 144 µg/m^3 in contrast to between 0.29 and 2.0 µg/m^3 for the other worker categories. All worker categories had some individual workers with elevated inhalable lead fractions far exceeding the new ECHA RAC proposed occupational exposure limit (OEL) of 3 µg/m^3. Total chromium levels were also elevated in lead battery workers in comparison to the other four worker categories. Respirable chromium air fractions were much lower than the inhalable air fractions. It is important to note that analysis was for total chromium and not Cr(VI). In general, the cadmium air results are considered low, apart from lead battery workers, where the median was over half the OEL of 1 µg/m^3. However, elevated cadmium air concentrations from individual workers who did exceed this OEL were observed in workers from white goods,

Table 6

Statistical summary in µg/m^3 8 h TWA (Time Weighted Average) of the median, range and 95th percentile (P95) and number of samples (n =) for both the inhalable and respirable personal air samples for chromium, cadmium and lead in the five worker categories. Comparison with the current and proposed ECHA occupational exposure limit (OEL) values, where available, is presented.

	Air Fraction		Lead Battery	White Goods	Brown Goods	Metals & Plastics	Miscellaneous	Current OEL	Future or Proposed OELs
Total Chromium µg/m^3 8 h TWA	Inhalable	Median	6.7	0.77	0.23	0.61	0.15	5 As Cr(VI) # (From January 2025)	–
		Range	<LOQ – 8.1	0.002–9.3	<LOQ – 9.7	<LOQ - 6.2	<LOQ – 1.5		
		P95	*	6	5.6	*	*		
		n =	17	38	48	16	14		
	Respirable	Median	<LOQ	0.54	0.06	0.08	0.03	–	–
		Range	<LOQ	0.002–3.5	<LOQ – 5.4	0.06–0.9	<LOQ – 0.2		
		P95	*	2.1	5.1	*	*		
		n =	17	39	39	14	12		
Total Cadmium µg/m^3 8 h TWA	Inhalable	Median	0.61	0.02	0.07	0.14	0.01	1	–
		Range	<LOQ - 0.8	<LOQ – 9.2	<LOQ – 5.1	<LOQ - 12.5	<LOQ – 0.35		
		P95	*	3.8	2.9	*	*		
		n =	17	38	49	16	14		
	Respirable	Median	<LOQ	0.004	0.005	0.02	0.004	–	–
		Range	<LOQ – 0.8	<LOQ – 6.1	<LOQ – 3.2	<LOQ – 0.55	<LOQ – 0.01		
		P95	*	2.3	2.0	*	*		
		n =	17	39	46	16	15		
Total Lead µg/m^3 8 h TWA	Inhalable	Median	144	0.29	2.0	1.5	0.88	150	3 (from 2026)
		Range	75–1024	<LOQ – 94	0.02–53	0.3–281	0.04–37		
		P95	*	21	39	*	*		
		n =	17	38	48	16	14		
	Respirable	Median	24	0.52	0.27	0.5	0.05	–	–
		Range	9.5–202	0.002–64	0.004–37	0.05–7.2	0.004–1.4		
		P95	*	*	21.9	*	*		
		n =	17	12	39	14	12		

The presented OELs are for comparison only. Not all countries involved in this study will implement these European wide OELs if that country already has their own legally binding limits. LOQ = limit of quantification; * = Not enough samples ($n < 20$) to accurately calculate the 95th percentile; - = No respirable OEL available; # = There is no EU OEL for trivalent chromium (Cr(III)) and total chromium measurements in these tasks is likely to represent both Cr(III) and Cr(VI).

brown goods and metals and plastics but not lead battery or miscellaneous workers. Only white goods and brown goods workers had respirable air fraction results above the inhalable OEL for cadmium.

3.6.2. Hand wipes

The hand wipe sampling results are presented in Fig. 4 and exposure is compared against all workers pre shift hand wipe results. The results for brown goods, white goods and miscellaneous workers are presented for chromium, cadmium and lead. For dermal mercury exposure, only brown goods and miscellaneous workers are presented in Fig. 4 as there were less than 10 sample results from white goods and metals and plastics workers. Wipe samples were not available for lead battery workers. A maximum of five wipe samples were collected per worker and the results expressed as a total of these.

As with the air sampling results, the highest dermal exposures were seen for lead. White goods, brown goods and miscellaneous workers all had shift sum median results that were not significantly different from each other (47.8 ng/cm^2, 38.9 ng/cm^2 and 47.6 ng/cm^2, respectively), compared against the all-workers pre-shift median of 3.0 ng/cm^2. Mercury dermal exposure was the lowest with a median result of less than 0.5 ng/cm^2 for both brown goods and metals and plastics workers compared to the all-workers pre-shift median of 0.03 ng/cm^2. In terms of dermal exposure to worker categories, white goods workers showed the highest overall median dermal exposure results for chromium (9.6 ng/cm^2), cadmium (8.5 ng/cm^2) and lead (47.8 ng/cm^2). In contrast, miscellaneous workers showed the lowest median dermal exposure for chromium (2.77 ng/cm^2), cadmium (0.5 ng/cm^2) and mercury (0.19 ng/cm^2) but not for lead. It is important to note that whilst a maximum of 47 brown goods workers had their dermal exposure results reported, only 12 were reported for white goods workers and 15 for miscellaneous workers, therefore comparisons should be interpreted cautiously.

3.7. Correlation among exposure markers

The Heatmaps of Spearman's correlation coefficients (r_s) between exposure markers for chromium, cadmium, mercury and lead are presented in Fig. 5. In addition, the number of pairs of samples (n) for each pair of exposure markers is also shown on the heatmaps. Correlation coefficients for less than 10 pairs of samples are not shown.

When comparing external exposure markers for chromium, cadmium, mercury and lead, moderate to strong positive correlations ($r_s > 0.6$) were observed between inhalable and respirable airborne fractions. In addition, airborne metal levels showed generally high ($r_s > 0.6$) correlation with hand contamination, except for mercury.

Strong positive correlations ($r_s > 0.72$) were observed between airborne lead levels (inhalable and respirable) and internal lead biomarkers (whole blood, urine and hair). In addition, internal lead biomarkers (whole blood and urine) showed moderate correlations with hand contamination ($r_s = 0.53$ and 0.56, respectively). Correlations between external and internal exposure markers for chromium, cadmium and mercury were generally low ($|r_s| \leq 0.52$).

High positive correlations ($r_s > 0.81$) were observed among internal lead biomarkers (whole blood, urine and hair). Correlations among internal exposure markers for chromium, cadmium and mercury were low ($|r_s| \leq 0.51$). Chromium only showed strong or moderate correlations between respirable and inhalable air and between air samples and hand wipes.

4. Discussion

The increasing global production of e-waste is a significant issue. Monitoring techniques are vital for assessing the efficacy of control measures in workplace safety, to ensure exposure levels stay within acceptable limits. Measuring workplace exposure levels can identify when control measures (for example, PPE or local exhaust ventilation (LEV)), are not adequately protecting workers, allowing for workplace intervention and improvements. This study aimed to identify and raise awareness of potential hazards of exposure to chromium, cadmium, mercury and lead in the European e-waste sector, and to ensure a sustainable practice of e-waste recycling both at current levels and in the

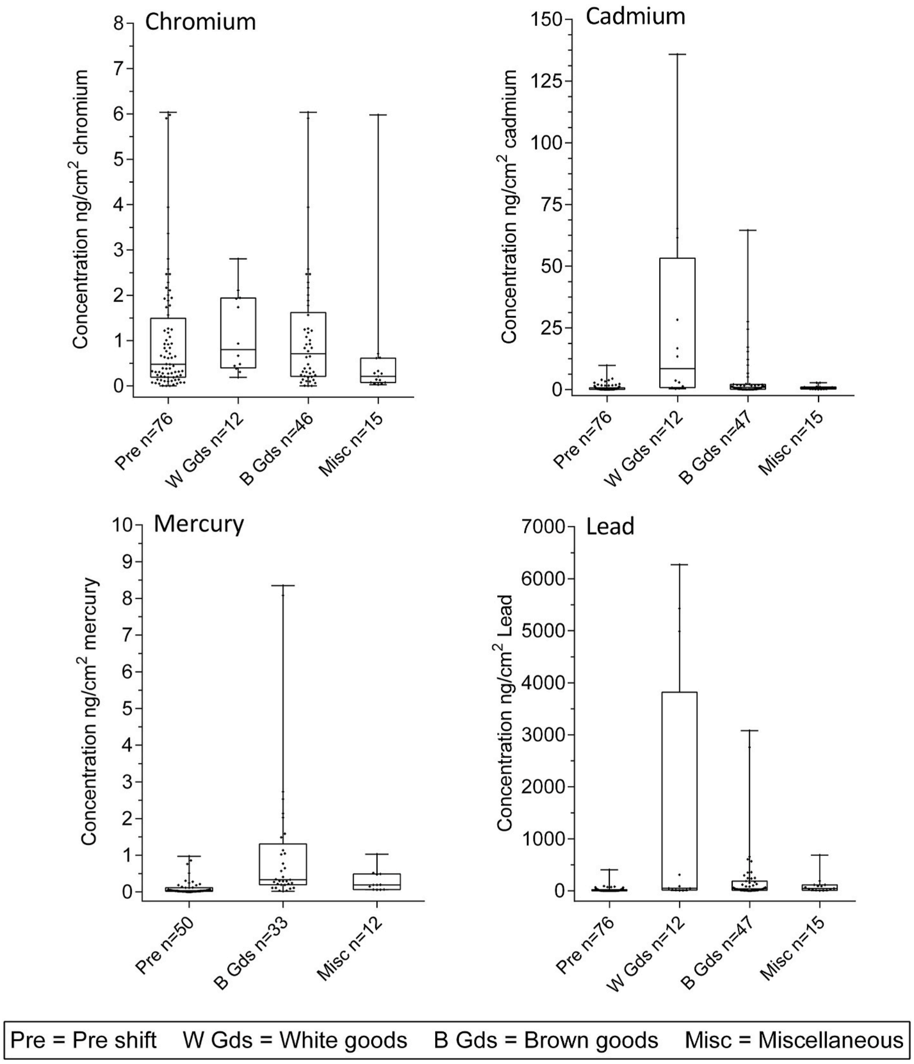


Fig. 4. Box and Whiskers plots chromium, cadmium, mercury and lead in hand wipes for White Goods, Brown Goods and Miscellaneous workers. Pre shift are all workers pre shift hand wipe results. The worker categories represent the sum of hand wipes taken across the shift. Box plots: Bottom and top represent the 25th and 75th percentiles, whilst the horizontal line is the median. The lower and upper end of the whiskers represent the minimum and maximum, the dots represent each individual result.

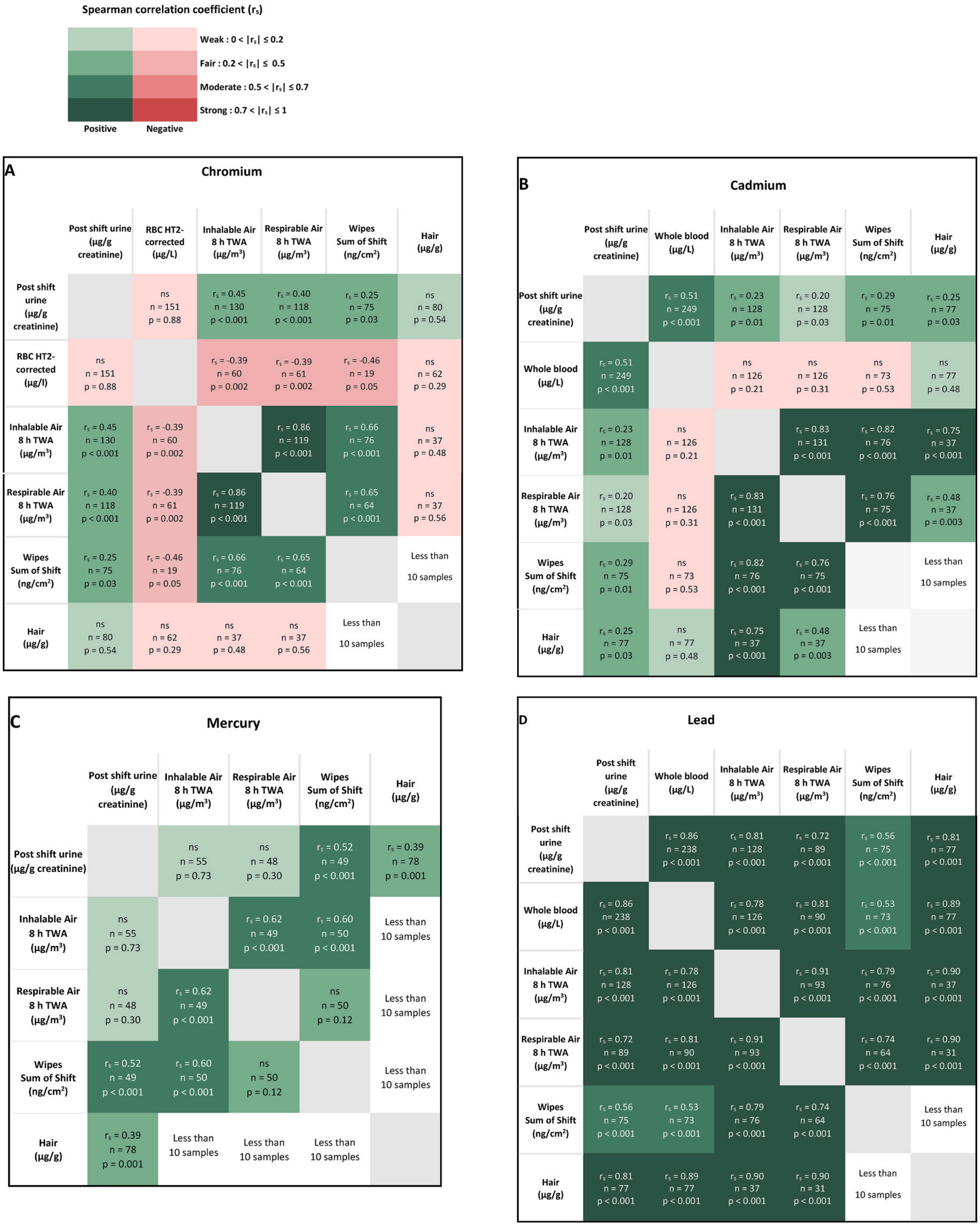
future as the recycling capability increases at a European level.

This study primarily focused on human biomonitoring but also included the collection of industrial hygiene samples, namely air, hand wipes and settled dust samples, to support the interpretation of the results. The human biomonitoring results in this study indicate work-related exposure predominantly to lead and to a lesser extent cadmium and mercury.

Please note that the guidance values and limits values used in this discussion are for comparison purposes only. Not all countries in this study adopt or use one single limit or guidance value for each element, with many countries having their own legally binding limits and values (for example inorganic lead).

4.1. Chromium

The urinary chromium results showed that occupational exposure to chromium in e-waste processing is generally low. There is no guidance value consensus in Europe for urinary chromium in occupationally exposed workers. As Cr (VI) is a carcinogen, Germany has an EKA (biological equivalent to inhalation exposures for carcinogens) of 20 μg/L approximately 14.7 μg/g creatinine and a background biological reference value (BAR) of 0.6 μg/L approximately 0.45 μg/g creatinine (DFG – Deutsche Forschungsgemeinschaft, 2024). No participant had a urinary chromium result exceeding the German EKA value, and only 19 % of the occupationally exposed workers exceeded the BAR. A German e-waste study by Gerding et al., (2021), also reported low levels of chromium exposure amongst its workers with a urinary chromium median and P95 of 0.08 μg/g creatinine and 5.0 μg/g creatinine respectively. The worker tasks in Gerding's study included disassembly of flat-screen and tube display monitors plus disassembly and sorting of small electronic devices. The median and P95 in this study for Brown Goods workers (which included televisions and monitors) were 0.21 μg/g creatinine and 0.62 μg/g creatinine, respectively. Despite urinary results being low, the personal air sampling results of lead battery workers was elevated in comparison to the other four worker categories. However, the air results are for total chromium indicating they represent a combination of both trivalent chromium (Cr(III)) and Cr(VI) and therefore cannot be compared against an OEL which is specific to Cr(VI) only. Unfortunately, hand wipe samples were not available from lead battery workers to determine if lead battery worker's dermal exposure was also elevated. Low exposure results are further supported by the weak and fair correlation analysis of the industrial hygiene and biomonitoring results. One explanation for the low urinary results and elevated air results could be that the presence of Cr(VI) is low in



A Chromium

	Post shift urine (µg/g creatinine)	RBC HT2-corrected (µg/L)	Inhalable Air 8 h TWA (µg/m^3)	Respirable Air 8 h TWA (µg/m^3)	Wipes Sum of Shift (ng/cm^2)	Hair (µg/g)
Post shift urine (µg/g creatinine)		ns n = 151 p = 0.88	r_s = 0.45 n = 130 p < 0.001	r_s = 0.40 n = 118 p < 0.001	r_s = 0.25 n = 75 p = 0.03	ns n = 80 p = 0.54
RBC HT2-corrected (µg/l)	ns n = 151 p = 0.88		r_s = -0.39 n = 60 p = 0.002	r_s = -0.39 n = 61 p = 0.002	r_s = -0.46 n = 19 p = 0.05	ns n = 62 p = 0.29
Inhalable Air 8 h TWA (µg/m^3)	r_s = 0.45 n = 130 p < 0.001	r_s = -0.39 n = 60 p = 0.002		r_s = 0.86 n = 119 p < 0.001	r_s = 0.66 n = 76 p < 0.001	ns n = 37 p = 0.48
Respirable Air 8 h TWA (µg/m^3)	r_s = 0.40 n = 118 p < 0.001	r_s = -0.39 n = 61 p = 0.002	r_s = 0.86 n = 119 p < 0.001		r_s = 0.65 n = 64 p < 0.001	ns n = 37 p = 0.56
Wipes Sum of Shift (ng/cm^2)	r_s = 0.25 n = 75 p = 0.03	r_s = -0.46 n = 19 p = 0.05	r_s = 0.66 n = 76 p < 0.001	r_s = 0.65 n = 64 p < 0.001		Less than 10 samples
Hair (µg/g)	ns n = 80 p = 0.54	ns n = 62 p = 0.29	ns n = 37 p = 0.48	ns n = 37 p = 0.56	Less than 10 samples	

B Cadmium

	Post shift urine (µg/g creatinine)	Whole blood (µg/L)	Inhalable Air 8 h TWA (µg/m^3)	Respirable Air 8 h TWA (µg/m^3)	Wipes Sum of Shift (ng/cm^2)	Hair (µg/g)
Post shift urine (µg/g creatinine)		r_s = 0.51 n = 249 p < 0.001	r_s = 0.23 n = 128 p = 0.01	r_s = 0.20 n = 128 p = 0.03	r_s = 0.29 n = 75 p = 0.01	r_s = 0.25 n = 77 p = 0.03
Whole blood (µg/L)	r_s = 0.51 n = 249 p < 0.001		ns n = 126 p = 0.21	ns n = 126 p = 0.31	ns n = 73 p = 0.53	ns n = 77 p = 0.48
Inhalable Air 8 h TWA (µg/m^3)	r_s = 0.23 n = 128 p = 0.01	ns n = 126 p = 0.21		r_s = 0.83 n = 131 p < 0.001	r_s = 0.82 n = 76 p < 0.001	r_s = 0.75 n = 37 p < 0.001
Respirable Air 8 h TWA (µg/m^3)	r_s = 0.20 n = 128 p = 0.03	ns n = 126 p = 0.31	r_s = 0.83 n = 131 p < 0.001		r_s = 0.76 n = 75 p < 0.001	r_s = 0.48 n = 37 p = 0.003
Wipes Sum of Shift (ng/cm^2)	r_s = 0.29 n = 75 p = 0.01	ns n = 73 p = 0.53	r_s = 0.82 n = 76 p < 0.001	r_s = 0.76 n = 75 p < 0.001		Less than 10 samples
Hair (µg/g)	r_s = 0.25 n = 77 p = 0.03	ns n = 77 p = 0.48	r_s = 0.75 n = 37 p < 0.001	r_s = 0.48 n = 37 p = 0.003	Less than 10 samples	

C Mercury

	Post shift urine (µg/g creatinine)	Inhalable Air 8 h TWA (µg/m^3)	Respirable Air 8 h TWA (µg/m^3)	Wipes Sum of Shift (ng/cm^2)	Hair (µg/g)
Post shift urine (µg/g creatinine)		ns n = 55 p = 0.73	ns n = 48 p = 0.30	r_s = 0.52 n = 49 p < 0.001	r_s = 0.39 n = 78 p = 0.001
Inhalable Air 8 h TWA (µg/m^3)	ns n = 55 p = 0.73		r_s = 0.62 n = 49 p < 0.001	r_s = 0.60 n = 50 p < 0.001	Less than 10 samples
Respirable Air 8 h TWA (µg/m^3)	ns n = 48 p = 0.30	r_s = 0.62 n = 49 p < 0.001		ns n = 50 p = 0.12	Less than 10 samples
Wipes Sum of Shift (ng/cm^2)	r_s = 0.52 n = 49 p < 0.001	r_s = 0.60 n = 50 p < 0.001	ns n = 50 p = 0.12		Less than 10 samples
Hair (µg/g)	r_s = 0.39 n = 78 p = 0.001	Less than 10 samples	Less than 10 samples	Less than 10 samples	

D Lead

	Post shift urine (µg/g creatinine)	Whole blood (µg/L)	Inhalable Air 8 h TWA (µg/m^3)	Respirable Air 8 h TWA (µg/m^3)	Wipes Sum of Shift (ng/cm^2)	Hair (µg/g)
Post shift urine (µg/g creatinine)		r_s = 0.86 n = 238 p < 0.001	r_s = 0.81 n = 128 p < 0.001	r_s = 0.72 n = 89 p < 0.001	r_s = 0.56 n = 75 p < 0.001	r_s = 0.81 n = 77 p < 0.001
Whole blood (µg/L)	r_s = 0.86 n= 238 p < 0.001		r_s = 0.78 n = 126 p < 0.001	r_s = 0.81 n = 90 p < 0.001	r_s = 0.53 n = 73 p < 0.001	r_s = 0.89 n = 77 p < 0.001
Inhalable Air 8 h TWA (µg/m^3)	r_s = 0.81 n = 128 p < 0.001	r_s = 0.78 n = 126 p < 0.001		r_s = 0.91 n = 93 p < 0.001	r_s = 0.79 n = 76 p < 0.001	r_s = 0.90 n = 37 p < 0.001
Respirable Air 8 h TWA (µg/m^3)	r_s = 0.72 n = 89 p < 0.001	r_s = 0.81 n = 90 p < 0.001	r_s = 0.91 n = 93 p < 0.001		r_s = 0.74 n = 64 p < 0.001	r_s = 0.90 n = 31 p < 0.001
Wipes Sum of Shift (ng/cm^2)	r_s = 0.56 n = 75 p < 0.001	r_s = 0.53 n = 73 p < 0.001	r_s = 0.79 n = 76 p < 0.001	r_s = 0.74 n = 64 p < 0.001		Less than 10 samples
Hair (µg/g)	r_s = 0.81 n = 77 p < 0.001	r_s = 0.89 n = 77 p < 0.001	r_s = 0.90 n = 37 p < 0.001	r_s = 0.90 n = 31 p < 0.001	Less than 10 samples	

Fig. 5. Heatmaps of Spearman correlation coefficients (r_s) for the different biological matrices and industrial hygiene samples for A. chromium, B. cadmium, C. mercury and D. lead. The size of a correlation is classified into following 4 categories: weak, fair, moderate and strong. Positive correlation coefficients are shown in shades of green, while negative correlations in shades of red as indicated in legend at top of figure. N is the number of couples of samples. Note that r_s for less than 10 pairs of samples are not shown. A non-significant correlation is indicated by 'ns'. P-values of <0.05 were considered statistically significant.

recycling processes, and the air results obtained are reflective of Cr(III), but due to its poor absorption in comparison to Cr(VI), is not represented in the urine samples.

4.2. Cadmium

The measurement of occupational exposure to cadmium in a blood or urine sample is difficult to interpret. Whilst blood cadmium indicates recent exposure over the previous couple of months, urinary cadmium reflects overall body burden, with a biological half-life of over 2 decades (ATSDR 2012; Hoet et al., 2021). It is also important to note that urinary cadmium will reflect only a small fraction of the total body burden as it binds to small proteins resulting in a constant cycle of filtration and reabsorption by the kidneys rather than being fully eliminated in the urine (Stajnko et al., 2017). As this accumulation of cadmium increases and exceeds what is termed the critical concentration, renal damage and dysfunction occurs meaning cadmium is no longer reabsorbed and urinary cadmium levels suddenly rise (Aitio et al., 2007). Biomonitoring of recent occupational exposure to cadmium requires a blood sample, where it should be possible to observe changes in response to workplace interventions or improvements. A urine sample can also be effective in biomonitoring of occupational exposure to cadmium, especially for monitoring the critical concentration. Therefore, sometimes especially with workers who have long-term exposure to cadmium it is recommended that both blood and urine concentrations are measured, and the results to be considered together (HSE – Health and Safety Executive, 2021). The biological exposure index (BEI®) guidance value by the American Conference of Governmental Industrial Hygienists (ACGIH) is 5 μg/g creatinine (ACGIH – American Conference of Governmental Industrial Hygienists, 2023), and the EU Scientific Committee on Occupational Exposure Limits (SCOEL) BLV is 2 μg/g creatinine (SCOEL – Scientific Committee on Occupational Exposure Limits, 2014). ECHA's RAC is recommending a reduction in the BLV to 1 μg/g creatinine (ECHA – European Chemicals Agency, 2021). Three of the urinary cadmium samples from brown goods workers exceeded the recommended BLV of 1 μg/g creatinine, none exceeded the existing BLV of 2 μg/g creatinine. In addition to this, only one blood cadmium result from a battery worker was above the BEI® guidance value for cadmium in blood of 5 μg/L (ACGIH – American Conference of Governmental Industrial Hygienists, 2023), but their corresponding pre and post urine samples were below the background German BAR of 0.8 μg/L (approx. – 0.8 μg/g creatinine) (DFG – Deutsche Forschungsgemeinschaft, 2024). The German BAR for cadmium in blood is < 1 μg/L (DFG – Deutsche Forschungsgemeinschaft, 2024), and 47 workers across all five categories were above this. It is well documented that there is a positive contribution to blood cadmium levels from smoking, and the cadmium blood BAR of <1 μg/L is based on non-smokers. E-waste studies by Gerding et al. (2021) and Julander et al. (2014) both reported higher levels of cadmium in smokers. Table 5 and the strong statistically significant difference outlined in Section 3.4 of the results indicates a contribution of cadmium exposure in smokers. Fig. 6 shows the cadmium in whole blood results of smokers and non-smokers, demonstrating that the blood cadmium results for the smoking workers is higher than the smoking controls, indicating that not all of the cadmium exposure found in the exposed workers is a direct consequence of smoking. However, there were only 11 smoking controls, and a bigger cohort would be required for an accurate comparison. In addition, of the 47 workers with a blood cadmium result exceeding 1 μg/L, thirty-nine were smokers, two were former smokers and six were non-smokers. It is important to note it was not recorded in the questionnaire which brands of cigarette were smoked by the workers or if the non-smokers lived in a smoking or non-smoking home. In contrast, four of the control group workers also exceeded the blood cadmium reference value, three of which were smokers, the fourth did not disclose their smoking status. ECHA's current inhalable OEL for cadmium is 1 μg/m^3 alongside a BLV of 2 μg/g creatinine. As stated above no urinary cadmium results exceeded 2 μg/g creatinine, and only 13 out of 133 inhalable air samples were above the OEL of 1 μg/m^3.

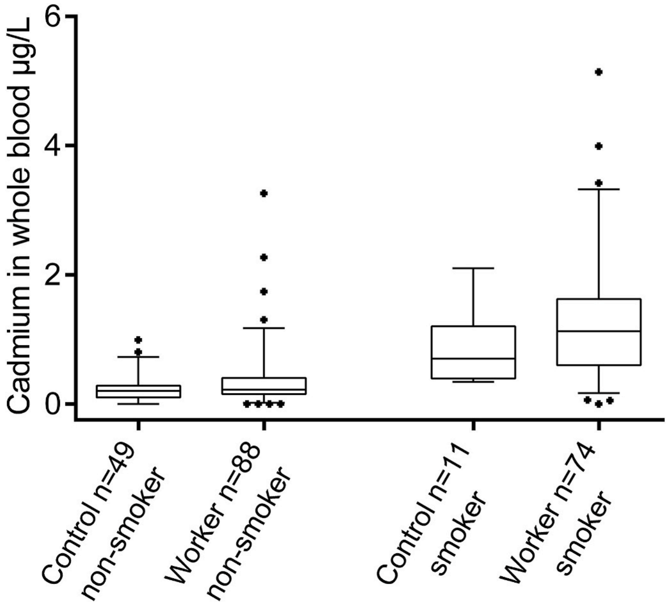


Fig. 6. Box and Whiskers plot for cadmium in whole blood of both the All-Control group and the occupationally exposed workers comparing non-smokers and cigarette smokers. Box plots: Bottom and top represent the 25th and 75th percentiles, whilst the horizontal line is the median. The lower and upper end of the whiskers represent the 5th and 95th percentile.

The different exposure durations reflected in blood cadmium and urinary cadmium, should be borne in mind when considering the correlations between exposure markers. In our study, low correlations were observed between external exposure and both urine and blood exposure. In addition, a moderate correlation between cadmium in blood and urinary cadmium was observed. Although similar correlations have been noted already in earlier studies, discrepancies with reported correlations in literature were also observed. These discrepancies are probably related to the difference in the occupational settings explored and consequently the kinetics of the metals in urine or blood, suggesting the need for longer follow-up in future human biomonitoring studies within the e-waste recycling sector.

4.3. Mercury

Although the urinary mercury results showed some occupational exposure for brown goods workers and a single elevated result for a white goods worker, in general the medians and P95s were comparable to the All-controls group. Based on six published background reference range studies, the range for mercury P95 values was between 0.96 and 2.8 μg/g creatinine (Heitland and Köster, 2021; NHANES – National Health and Nutrition Examination Survey, 2022; Frery et al., 2011; Hoet et al., 2013; Morton et al., 2014; Castaño et al., 2019). Consumption of seafood is the main source of mercury (in the form of methyl mercury (MeHg)) exposure in the general population. Elimination of MeHg in humans occurs primarily in faeces and bile, but it has been suggested that up to 10 % is via urine in the form of inorganic mercury (Akerstrom et al., 2017; Boerleider et al., 2017), which is the probable reason for the slight variations observed both in the different published background references ranges stated above and both the exposed workers and control groups. Countries where fish consumption is much higher, or countries where samples were collected from more coastal regions could have higher urinary mercury background levels (Petrova et al., 2020). In this study, control samples from Portugal showed higher urinary mercury values when compared to controls from all the other countries ($p = 0.001$). As mentioned above and in Table 4, section 3.2.3 of the results section, some elevated results were found within brown goods workers, which might be expected as the category of brown goods workers included workers recycling television/computer screens and fluorescent light bulbs/lamps which are the main sources of mercury in e-waste (Aubrac et al., 2022; Gul et al., 2020; Zimmermann et al., 2014). However, no results exceeded either the German Biological Tolerance Value (BAT) of 25 μg/g creatinine (DFG – Deutsche Forschungsgemeinschaft, 2024) or the European BLV of 30 μg/g creatinine (SCOEL – Scientific Committee on Occupational Exposure Limits, 2014), and 98 % of the urinary mercury results were below the German Environment Agency (GEA) Human Biomonitoring values (HBM1) background reference value of 5 μg/g creatinine (GEA – German Environment Agency, 2023). A French background levels study report a median of 0.6 μg/g and P95 of 2.18 μg/g for adult mercury levels in hair (Oleko et al., 2024). In addition, Scotland has a reference range for mercury in hair of <2 μg/g (STEMDRL – Scottish Trace Element and Micronutrient Diagnostic and Research Laboratory, 2024). Both are like the mercury hair results from the All-Control group with a median of 0.72 μg/g and P95 of 1.72 μg/g. Only hair samples from lead battery workers were elevated for mercury, with 23 out of 24 hair samples above the All-Control group median and 12 exceeding the French and Scottish reference ranges stated above. No significant differences were found between the urinary mercury results from lead battery workers compared to other workers. Past fish consumption cannot be ruled out as the source of the elevated mercury hair results among these workers. The hair from people who consume fish have an elevated total mercury content in comparison to those who do not eat fish (Rumiantseva et al., 2024). This is because hair absorbs MeHg from circulating blood, making it the dominant species in hair (Petrova et al., 2020). As stated in 3.6.1 of the results section, the air monitoring sampling strategy was not suitable for the collection of mercury vapours. Therefore, the mercury results for air (both inhalable and respirable fractions) will not be representative of airborne exposures. For this reason, many of the air samples collected were not analysed for mercury, as shown by the low sample numbers per worker category in Table S7 of the Supplementary information. The number of hand wipes collected for dermal exposure is also low per worker category. Therefore, no comparisons can be made for mercury exposure between the biological monitoring results and the industrial hygiene results.

4.4. *Lead*

The urinary and whole blood lead results mirrored each other with lead battery workers exhibiting the highest lead exposure, followed by metals and plastics workers. Urinary lead analysis has been commonly used as a biomarker for organic lead which is quickly excreted in urine as diethyl lead (ECHA – European Chemicals Agency, 2020; NTP – National Toxicology Program, 2012). However, inorganic lead can also be excreted in urine reflecting recent exposure whereas blood lead reflects longer term exposure and is the favoured biological matrix for biomonitoring (ECHA – European Chemicals Agency, 2020; NTP – National Toxicology Program, 2012). Since organic lead exposure is unlikely, urinary lead in this study was interpreted to reflect recent exposure to inorganic lead. It must be remembered that guidance values for lead in urine are relevant to organic and not inorganic lead. It must also be noted that although correlations have been found with urinary and blood lead, linear correlation models have shown high variance and uncertainty (ECHA – European Chemicals Agency, 2020). In this study there was a strong correlation between urine and blood levels ($p < 0.001$). Due to lead toxicity and vast array of health effects, biomonitoring of occupational exposure to inorganic lead is regulated by law. In Europe, the BLV was 700 μg/L (Council of the European Union, 1998) with some countries holding their own lower legally binding limits and guidance values (HSE – Health and Safety Executive, 2002; Bolt et al., 2020; SER – Social and Economic Council of the Netherlands, 2007). Both SCOEL and ACGIH have both recommended an action limit of 300 μg/L (SCOEL – Scientific Committee on Occupational Exposure Limits, 2014; ACGIH – American Conference of Governmental Industrial Hygienists, 2023). However, it has been proposed that the 700 μg/L European binding BLV for lead be reduced to 150 μg/L (EUR-LEX, 2023). This limit value is based on neurological effects in adults but does not cover developmental neurotoxicology for which no threshold for a safe level can be currently given (ECHA – European Chemicals Agency, 2020b). The recent opinion of ECHA's RAC concludes that women of reproductive capacity are not included in this new BLV of 150 μg/L, and instead it is proposed that the blood lead level of women of reproductive capacity should not exceed the P95 reference value of the background population for that country (ECHA – European Chemicals Agency, 2020b), where national background reference ranges are not available it is recommended a Biological Guidance Value (BGV) of 45 μg/L not be exceeded. This is because inorganic lead is classed as a reprotoxic substance meaning it can have an effect on both fertility and the development of the foetus of offspring of female workers (EUR-LEX, 2024). The German BAR is also lower for women (30 μg/L) than it is for men (40 μg/L) (DFG – Deutsche Forschungsgemeinschaft, 2024). The reduction of the European binding BLV from 700 to 150 μg/L for lead was approved in February 2024. Due to the substantial reduction and time needed to implement risk-management measures a transitional BLV of 300 μg/L will apply until December 31, 2028 (EUR-LEX, 2024). Fig. 7 shows the workers exceeding the revised BLV of <150 μg/L, which accounts for 13 % of the workers who provided a blood sample, predominantly from lead battery workers. There were no exceedances of the proposed BLV from white good workers and the All-controls group. The 13 % also includes female workers. Of the twenty-three blood samples from female workers, eleven exceeded the German BAR for women of 30 μg/L for inorganic lead (DFG – Deutsche Forschungsgemeinschaft, 2024). In a similar study by Julander et al. (2014) in Sweden, not significantly different concentrations of lead in blood of e-waste workers ($n = 25$) were reported as in this study. They found a median of 33 μg/L (range was 7–240 μg/L) compared with the data from this study reported in Fig. 4, shows workers in lead battery recycling with blood lead values almost two-fold higher. However, the Swedish study did not include lead battery recycling and if the results from lead battery workers were removed from this study, the blood lead results from the other four worker categories would be comparable.

Like the urinary and blood results, the air sampling results for lead were elevated in all worker categories when compared against ECHA's RAC proposed occupational exposure limit (OEL) of 3 μg/m^3 (which will apply from 2026) (ILA – International Lead Association, 2004), with battery workers having both inhalable and respirable median values and range of results much higher than the other 4 worker categories. Miscellaneous workers had the lowest air results. Unfortunately, hand wipes were not available for battery workers, and so, in our study, white goods workers showed the highest dermal exposure to lead.

Strong correlations were observed between airborne lead and all biomarkers. Inhalation as the primary exposure route has been noted in earlier studies in the e-waste recycling sector (Julander et al., 2014). In

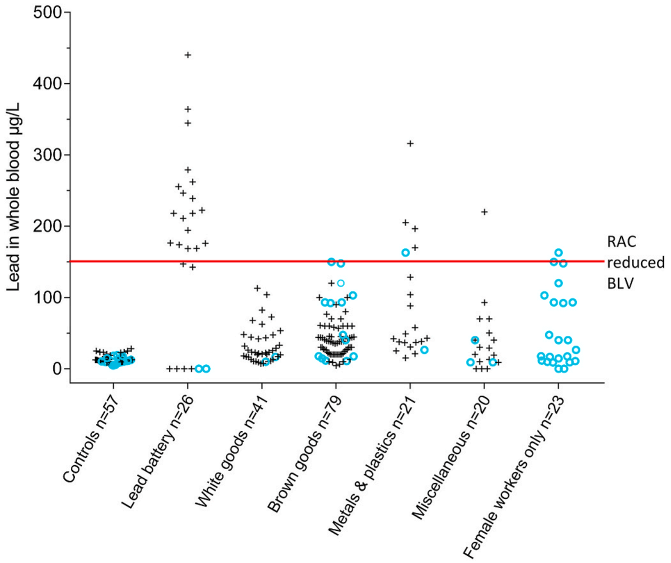


Fig. 7. Scatter plots showing the results of lead in whole blood in μg/L for each of the five worker categories and the All-controls group in addition to results of female workers only (and within the worker categories). It shows the results in comparison to The European Chemicals Agency's (ECHA) Risk Assessment Committee (RAC) proposed biological limit value (BLV). Female workers are represented by blue circles, and male workers by black crosses.

addition to inhalation exposure, the observed lead contamination in hand wipes may also contribute to the systemic exposure of e-waste workers to lead. In our study, we observed moderate correlations between urinary lead levels and wipe sample results. There are three potential explanations that may each, individually or combined, explain our observations. First, lead may be absorbed through the skin. However, such effects have only been reported through compromised skin at the workplace, e.g., due to physical and chemical damage (Kezic and Nielsen, 2009). Second, skin contamination could result in hand-mouth contact and ingestion is serving as a potential secondary uptake route (Sahmel et al., 2015). Third, it is possible that the observed association is not causal but merely reflects a common source of airborne particles that can be inhaled and may later settle on surfaces in the workplace, leading to skin exposure as indicated by our hand wipes results (Mielke et al., 2022; Parvez et al., 2024). This last explanation is supported by the fact that lead was the predominant element in settled dust and airborne fractions. This indicates that metals released in the environment by e-waste recycling activities may reach other workers in the surrounding areas. Strong correlations were also observed among lead biomarkers. This could be explained by slow excretion rate and consequently long-term accumulation of lead (NTP – National Toxicology Program, 2012), which also explains why no significant difference was observed between pre and post urine results. The observed correlations between external and internal exposure markers for lead, suggest that existing control measures may not sufficiently reduce worker exposure.

4.5. Strengths and limitations

Despite the advantage that this multi-centre human biomonitoring study gathered data on occupational exposure to chromium, cadmium, mercury and lead during e-waste processing or recycling in various European countries using harmonised protocols, this kind of multi-centre occupational study is also subject to challenges and limitations (Galea et al., 2021).

Although SOPs were established under HBM4EU to facilitate the collection of harmonised data, deviations occurred in the methods employed for gathering and analysing industrial hygiene samples. Methods for air sampling for mercury were not in place to ensure appropriate analysis. Additionally, LOQs for analysis of both biomonitoring and industrial hygiene samples varied among different laboratories which may also have influenced the interpretation of the results. Although the standardised practice of using average hand areas of 445 cm^2 per female hand and 535 cm^2 per male hand were used to express the results per cm^2 hand area, there is chance of small variability (US EPA – United States Environment Protection Agency, 2011).

The type and number of e-waste categories and controls covered by the sampling campaigns and the final numbers of measurements for the different exposure markers varied amongst the laboratories in the different countries. Both were dependent on workplace and country specific aspects, including availability and willingness of companies and workers to participate in the study, technical aspects and regulatory context.

Within this human biomonitoring study, hair samples were collected for the testing of hair as a material for occupational biomonitoring. Although the understanding of the hair results may be affected by the low number of available observations, the results supported findings from urine and blood data within this cohort. However, it is important to note that these results should be interpreted with caution, since hair is only considered an established biomarker for one of the four metals included in this study, namely mercury (Martinez-Morata et al., 2023). The use of hair for biomonitoring of lead, cadmium and chromium is still under discussion due to challenges such as contamination from the environment and artificial hair treatments (Martinez-Morata et al., 2023).

5. Conclusion

This study has produced new occupational exposure data for chromium, cadmium, mercury and lead in e-waste recycling workers across eight European countries. The results show evidence of work-related exposure to lead in all five e-waste categories of workers (principally lead battery workers) with high positive correlations between all lead markers of exposure (internal and external), including between the urine and blood results. This high correlation indicates that urine might have potential to be a suitable additional biological matrix for the exposure assessment of inorganic lead exposure. The exposure data presented, shows that current health and safety practices within the e-waste recycling industry, are not adequately protecting workers from exposure to lead. This elevated lead data indicates that worker exposure would most likely increase as e-waste recycling increases in the future. The lead exposure data reported also shows that follow up biological monitoring is required across all e-waste workers to help introduce and evaluate effectiveness of good working practices to reduce worker exposure and the risk of ill health in the future. This need will be compounded when ECHA implements the RAC's proposed reduction to the OEL (for air) and the BLV (for blood), particularly for female workers of reproductive capacity.

The results show to a lesser extent, some work-related exposure to cadmium and mercury. Cadmium exposure, like lead, was found in workers across all five categories of e-waste recycling. It is of interest that not all of the cadmium exposure found in the blood and urine levels was a direct consequence of smoking. Work-related exposure to mercury, although low-level, was found mainly in brown goods workers. Hair sampling has shown that it is not a reliable biological matrix for occupational exposure assessment of mercury at these low exposure levels due to past seafood consumption. The results show that chromium had the lowest work-related exposure.

This study has shown the use of biological monitoring to assess exposure in the e-waste recycling sector, and that continued repeated monitoring is not only essential for lead but also advisable for cadmium and mercury exposure. As there continues to be an increase in e-waste throughout Europe, driven by the Circular Economy Action Plan, there is a need to ensure that as the levels of recycling increase, worker's exposure is assessed using suitable monitoring strategies to help verify that exposure is adequately controlled. In future e-waste studies it would be advantageous to investigate exposure to additional elements such as lithium, antimony, cobalt and nickel.

CRediT authorship contribution statement

Elizabeth Leese: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Jelle Verdonck:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Simo P. Porras:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Jaakko Airaksinen:** Visualization, Data curation. **Radu C. Duca:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Karen S. Galea:** Writing – review & editing, Methodology, Conceptualization. **Lode Godderis:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Beata Janasik:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Selma Mahiout:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Carla Martins:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Inese Mārtiņsone:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Maria Mirela Ani:** Writing – review & editing, Methodology, Investigation. **An van Nieuwenhuyse:** Writing – review & editing, Methodology, Investigation. **Paul T.J. Scheepers:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Maria João Silva:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Susana Viegas:** Writing – review & editing,

Methodology, Investigation, Conceptualization. **Tiina Santonen:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Ethics

The study involves human subjects. Consent from subjects participating in the study was received prior to conducting the study. Study protocols have been approved by ethical review boards in each of the participating countries. The ethical boards reviewing and approving the study are as follows.

- Belgium: Approved by: Ethics Committee Research UZ/KU Leuven. Reference number: S64321, Authorization date: October 8, 2020;
- Finland: Coordinating ethics committee, HUS Joint Authority, Helsinki, Finland. Decision number HUS/1357/2021, dated June 2, 2021;
- Luxembourg: the National Research Ethics Committee, approved on the August 4, 2021, and the Ministry of Health approved on November 17, 2021 (Reference number: 83bx30c66);
- Latvia: Rīgas Stradiņš University Research Ethics Committee, approved on April 14, 2021 (Reference number: 22–2/250/2021);
- The Netherlands: the CMO Regio Arnhem Nijmegen, approved on January 20, 2021 (Reference number: 2020–7089; National registry: NL67044.091.18);
- Poland: Bioethical Committees at the Nofer Institute of Occupational Medicine; Approved on March 11, 2020 (Reference number 05/2020)
- Portugal: Ethical Committee of the National Institute of Health Dr. Ricardo Jorge (Ethics Committee for Health, INSA), authorized on the September 22, 2021) and Ethical Committee of the Lisbon School of Health Technology authorized on the March 13, 2020;
- UK: NHS (National Health Service) Health Research Authority, London – Brighton & Sussex Research Ethics Committee (reference number 21/PR/0194, project ID 287188).

Disclaimer

The contents, including any opinions and/or conclusions expressed of this manuscript, are those of the authors alone and do not necessarily reflect the opinions or policy of the organisations to which they are employed.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Elizabeth Leese reports financial support was provided by Horizon 2020) for Research and Innovation Programme. If there are other authors, they 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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.121892.

Data availability

Data will be made available on request.

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