CityU Scholars

Urinary metals and their associations with DNA oxidative damage among e-waste recycling workers in Hong Kong

Liao, Gengze; Weng, Xueqiong; Wang, Feng; Yu, Yanny Hoi Kuen; Arrandale, Victoria H.; Chan, Alan Hoi-shou; Lu, Shaoyou; Tse, Lap Ah

Published in:
Ecotoxicology and Environmental Safety

Published: 01/10/2024

Document Version:
Final Published version, also known as Publisher’s PDF, Publisher’s Final version or Version of Record

License:
CC BY-NC-ND

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1016/j.ecoenv.2024.116872

Publication details:
Liao, G., Weng, X., Wang, F., Yu, Y. H. K., Arrandale, V. H., Chan, A. H., Lu, S., & Tse, L. A. (2024). Urinary metals and their associations with DNA oxidative damage among e-waste recycling workers in Hong Kong. *Ecotoxicology and Environmental Safety*, *284*, Article 116872. https://doi.org/10.1016/j.ecoenv.2024.116872

Citing this paper
Please note that where the full-text provided on CityU Scholars is the Post-print version (also known as Accepted Author Manuscript, Peer-reviewed or Author Final version), it may differ from the Final Published version. When citing, ensure that you check and use the publisher's definitive version for pagination and other details.

General rights
Copyright for the publications made accessible via the CityU Scholars portal is retained by the author(s) and/or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights. Users may not further distribute the material or use it for any profit-making activity or commercial gain.

Publisher permission
Permission for previously published items are in accordance with publisher's copyright policies sourced from the SHERPA RoMEO database. Links to full text versions (either Published or Post-print) are only available if corresponding publishers allow open access.

Take down policy
Contact lbscholars@cityu.edu.hk if you believe that this document breaches copyright and provide us with details. We will remove access to the work immediately and investigate your claim.

Download date: 13/01/2025

Ecotoxicology and Environmental Safety 284 (2024) 116872

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Urinary metals and their associations with DNA oxidative damage among e-waste recycling workers in Hong Kong

Gengze Liao [a,b], Xueqiong Weng [a], Feng Wang [a,b], Yanny Hoi Kuen Yu [c], Victoria H. Arrandale [d], Alan Hoi-shou Chan [e], Shaoyou Lu [f,**], Lap Ah Tse [a,b,g,*]

[a] *JC School of Public Health and Primary Care, The Chinese University of Hong Kong, Hong Kong SAR, China*
[b] *The CUHK Centre for Public Health and Primary Care (Shenzhen) & Shenzhen Municipal Key Laboratory for Health Risk Analysis, Shenzhen Research Institute of the Chinese University of Hong Kong, Shenzhen, China*
[c] *Occupational Safety and Health Council, Hong Kong SAR, China*
[d] *Dalla Lana School of Public Health, University of Toronto, Toronto, Canada*
[e] *Department of Systems Engineering, City University of Hong Kong, Hong Kong SAR, China*
[f] *School of Public Health (Shenzhen), Shenzhen Campus of Sun Yat-sen University, Shenzhen, China*
[g] *Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Hong Kong SAR, China*

ARTICLE INFO

Edited by Renjie Chen

Keywords:
E-waste
Hong Kong
Metals
8-OHdG
Workers
Urine

ABSTRACT

Recycling electronic waste (e-waste) poses risks of metal exposure, potentially leading to health impairments. However, no previous study has focused on this issue in Hong Kong. Therefore, from June 2021 to September 2022, this study collected urine samples from 101 e-waste workers and 100 office workers in Hong Kong to compare their urinary levels of metals using ICP-MS. Among the 15 included metals (with detection rates above the 70 % threshold), eight showed significantly higher urinary concentrations (unit: μg/g creatinine) in e-waste workers compared to office workers: Li (25.09 vs. 33.36), Mn (1.78 vs. 4.15), Ni (2.10 vs. 2.77), Cu (5.81 vs. 9.23), Zn (404.35 vs. 431.52), Sr (151.33 vs. 186.26), Tl (0.35 vs. 0.43), and Pb (0.69 vs. 1.16). E-waste workers in Hong Kong generally exhibited lower metal levels than those in developing regions but higher than their counterparts in developed areas. The urine level of 8-hydroxy-2-deoxyguanosine (8-OHdG) was determined by HPLC-MS/MS, and no significant difference was found between the two groups. Multiple linear regression models revealed no significant association between individual metal and urinary 8-OHdG concentrations. However, the metal mixture was identified to marginally elevate the 8-OHdG concentrations (1.12, 95 %CI: 0.04, 2.19) by quantile g-computation models, with Mn and Cd playing significant roles in such effect. In conclusion, while the metal levels among Hong Kong e-waste workers compared favorably with their counterparts in other regions, their levels were higher than those of local office workers. This underscores the need for policymakers to prioritize attention to this unique industry.

1. Introduction

Electronic waste (e-waste) encompasses outdated and abandoned electronic devices, ranging from small items (e.g., cell phones) to large appliances (e.g., washing machines) (Widmer et al., 2005). Globally, e-waste generation totaled 53.6 million tons in 2019, with recycled materials from e-waste valued at approximately USD 57 billion (Forti et al., 2020). E-waste recycling primarily targets precious materials, notably precious metals like gold, silver, and copper, given that metals make up about 60 % of the net weight of most e-waste (Ding et al., 2019; Zeng et al., 2018). Additionally, proper e-waste management significantly supports the circular economy, mitigates environmental pollution, and safeguards public health by preventing the release of toxicants from e-waste (e.g., inorganic metals and organic pollutants) through mishandling such as open burning or landfill disposal (Rautela et al., 2021; Song and Li, 2015; Zeng et al., 2018).

---

* Correspondence to: JC School of Public Health and Primary Care, the Chinese University of Hong Kong, 4/F School of Public Health and Primary Care, Prince of Wales Hospital, Sha Tin, N.T., Hong Kong SAR, China.

** Correspondence to: School of Public Health (Shenzhen), Sun Yat-sen University, 1-215 West, Medical Park, Sun Yat-sen University Shenzhen Campus, 66 Gongchang Road, Guangming District, Shenzhen, China.

E-mail addresses: lushy23@mail.sysu.edu.cn (S. Lu), shelly@cuhk.edu.hk (L.A. Tse).

https://doi.org/10.1016/j.ecoenv.2024.116872
Received 26 June 2024; Received in revised form 30 July 2024; Accepted 9 August 2024

Metals are integral elements in various types of components in e-waste; for example, lead (Pb) and lithium (Li) in batteries, copper (Cu) in cables, and cadmium (Cd) in circuit boards (Song and Li, 2014a). During the e-waste recycling process, such as dismantling, shredding, extraction, and final disposal, these metals can be released into the surrounding environment (Robinson, 2009). Metals in the environmental matrix could be absorbed via dermal contact, inhalation, ingestion, and placental transfer, and accumulate in the human body when the rate of absorption exceeds excretion (Song and Li, 2014b). Previous studies documented elevated internal metal exposure levels among residents in the e-waste recycling areas and e-waste workers (Julander et al., 2014; Zeng et al., 2016). Many of these metals are redox-active and can generate reactive oxygen/nitrogen species, potentially causing damage to DNA, protein, and lipids when their production exceeds the capability of antioxidant defense systems and eventually induces chronic or acute adverse health effects (Chen et al., 2018; Jomova and Valko, 2011). Take Pb as an example, experimental and epidemiological studies demonstrated that Pb exposure, even at low doses, was associated with oxidative stress and a broad range of adverse health outcomes (Ahamed and Siddiqui, 2007; Lopes et al., 2016).

As one of the pivotal hubs linking China and the rest of the world, the e-waste recycling industry in Hong Kong possesses distinct characteristics compared to mainland China (Wong, 2018). In detail, Hong Kong generated approximately 153 kilotonnes of e-waste in 2019, amounting to 20.2 kg per capita, which was nearly three times the global average (Forti et al., 2020). Recent legislation implemented by the local and Chinese authorities in 2018 has intensified the workload of frontline e-waste workers in Hong Kong (Wong, 2018), necessitating timely handling of the growing e-waste volume. Despite the occupational hazards associated with e-waste recycling, no study has yet assessed the burden of metal exposure among e-waste workers in Hong Kong, particularly in the specific sectors lacking adequate occupational safety and health resources. Therefore, this study aimed to evaluate the urinary metal levels among e-waste workers in Hong Kong, providing essential data for local occupational hygiene monitoring and serving as a reference to fill global research gaps. Additionally, this study assesses the potential health risks of metal exposure by investigating the associations between metals and the marker of oxidative DNA damage, 8-hydroxy-2-deoxyguanosine (8-OHdG).

2. Materials and methods

2.1. Study design and participants

A total of 218 participants were enrolled in this study between June 2021 and September 2022 in Hong Kong, comprising 109 local e-waste workers and an equal number of age-matched office workers who served as a control group (Liao et al., 2024). Research ethics approval was obtained from the Joint Chinese University of Hong Kong-New Territories East Cluster Clinical Research Ethics Committee (CREC No.: 2020.039). Before commencement, all the participants provided informed consent.

Trained research assistants administered standard questionnaires to collect the sociodemographic and occupational information from participants. Both e-waste and office workers reported details including age, sex, smoking and drinking habits, education level, marital status, monthly family income, residential address, and the frequency of consuming specific food (e.g., marine fish, bacon, et al.). Residential air pollution levels (categorized as high- or low-polluted) were determined based on the pollutant concentrations (NO_2, PM_{10}, and $PM_{2.5}$) from the monitoring stations near their residential addresses. The pollution levels were ranked across all districts in Hong Kong, with ranks for NO2, PM10, and PM2.5 assigned to participants in specific districts. These ranks were summed up and used to categorize each participant as residing in a high- or low-polluted area based on the median rank value. For example, if NO2, PM10, and PM2.5 levels in Shatin were ranked 10th, 8th, and 9th among all districts, participants from Shatin would have a total rank of $10 + 8 + 9$. If this total rank exceeded the median value among all districts, Shatin was classified as a low-polluted area.

Additional information specific to e-waste workers included job characteristics such as job title, duration of employment in the e-waste industry, weekly working hours, and details about their employing entity and job rotation system.

While 218 questionnaires were collected, 201 urinary samples were available for chemical analysis (i.e., 101 from e-waste workers and 100 from office workers), as some participants did not provide sufficient (50 mL) first-spot morning urine samples when returning their research materials. The collection of morning first-spot urine samples helps to minimize the influences of water drinking during the daytime and also accounts for the variations in work shifts among participants. All urine samples were promptly stored at −80°C within two hours of collection.

2.2. Chemicals and reagents

To analyze the concentrations of metals in urine samples, we utilized an inductively coupled plasma mass spectrometer (ICP-MS, Agilent Technologies, Inc., Santa Clara, CA, USA), following the methodologies outlined in previous studies (Liu et al., 2022; Yang et al., 2020). Urinary creatinine levels were quantified directly by the Roche Cobas 8000 system (Roche Diagnostics, Mannheim, Germany). The concentration of 8-OHdG was tested by a 20 A high-performance liquid chromatography system (HPLC; Shimadzu, Kyoto, Japan), which was coupled with a Q-Trap 5500 tandem mass spectrometer (MS/MS; Applied Biosystems, Foster City, CA, USA).

The multielement standard solution, which included containing Li, vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), arsenic (As), selenium (Se), rubidium (Rb), strontium (Sr), cadmium (Cd), cesium (Cs), Ba (barium), Mercury (Hg), thallium (Tl), lead (Pb), and uranium (U), as well as the internal standard solution for ICP-MS (containing scandium, germanium, rhodium, and rhenium) were sourced from Agilent Technologies (Santa Clara, CA, USA). The internal standards of 8-OHdG, specifically $^{15}N_5$–8-OHdG (98 % purity) and 8-OHdG (>97 % purity), were obtained from Cambridge Isotope Laboratories (Andover, MA, USA) and Sigma Aldrich (St. Louis, MO, USA), respectively. Additionally, while an ultra-pure analytical grade nitric acid (68 %) was purchased from Sigma-Aldrich (Darmstadt, Germany), formic acid (HPLC grade) and solid-phase extraction (SPE) cartridges (CNW P-WAX, 60 mg/3 mL) were purchased from Anpel (Shanghai, China).

2.3. Sample analysis and quality control

To prepare the samples for analysis, 0.25 mL of thawed urine was acidified with 4.75 mL of 1 % nitric acid and thoroughly mixed. Deionized water (0.25 mL) served as the reagent blank. The target metals in the urine were measured using ICP-MS following the Chinese national standard GBZ/T 308–2018. Detailed optimized parameters for the instrument analysis are provided in Supplementary Table 1.

The determination of urinary 8-OHdG concentrations followed established protocols from previous studies (Wu et al., 2023; Zhao et al., 2022). In short, a 2 mL urine sample was mixed with 10 μL $^{15}N_5$–8-OHdG (0.25 ng/μL) and 12 μL formic acid. The mixture was then loaded into the CNW P-WAX SPE cartridge for separation and subsequently analyzed by HPLC-MS/MS after being dissolved in 400 μL of methanol.

To prevent background contamination from glassware, polyethylene containers were used to measure target metals. The stability of instrument responses was verified using an internal standard solution with moderate concentrations, with all relative standard deviations (RSD) remaining below 10 %. Recovery experiments were conducted with pooled urine samples spiked with reference standards of metals (20 ng each), yielding recoveries ranging from 89.12 % to 134.58 %. The urinary concentrations of the target analytes were determined using calibration curves spanning from 0.01 to 50.0 ng/mL, with regression coefficients (R2) exceeding 0.99.

2.4. Statistical analysis

The limit of quantification (LOQ) was defined as ten times the background signal of the matrix blank. For chemicals with concentrations below the LOQ, half of the LOQ value was used as a substitute. The concentrations of the target analytes were then normalized by urinary creatinine (ug/g creatinine).

The distributions of selected variables were presented as mean ± SD for continuous variables with normal distribution, median (IQR) for those with skewed distribution, and n (%) for categorical variables. Differences between e-waste workers and office workers were analyzed using different statistical methods depending on the data type. For normally distributed continuous variables, an independent t-test was used. The Mann-Whitney test was applied for non-normally distributed variables. The chi-square test was employed to evaluate differences in categorical variables.

The correlations among the tested metals were assessed by Spearman's correlation analysis. To investigate the associations between each metal and the levels of 8-OHdG, multiple linear regression models were employed. These models adjusted for confounding factors identified through a directed acyclic graph (Textor et al., 2016), including sex, age, job types, smoking habits, residential air pollution levels, and the frequency of consuming marine fish. Quantile g-computation (QGC) was subsequently used to assess the effects of metal mixtures on 8-OHdG levels, utilizing the R package "qgcomp". QGC, based on parametric g-computation, employs a generalized linear model approach to evaluate the combined effects of the mixture by simultaneously increasing one quartile of all elements (Keil et al., 2020). This method also provides insights into the directions and weights of the components' impacts on the target outcome. Chemicals with estimated weights larger than 0.05 were considered the principal contributing factors to the mixture effect (Duc et al., 2022). A p-value of 0.05 or lower in a two-sided test was considered statistically significant. All the analyses were performed using R 4.2.2.

3. Results

3.1. Sociodemographic differences between e-waste and office workers

As shown in Table 1, the distributions of age and sex were similar between the e-waste and office workers. However, a higher proportion of e-waste workers reported smoking habits and were married compared to their office counterparts. The e-waste workers in this study were primarily from the disadvantaged population, characterized by lower education levels, lower household income, and residence in areas with high air pollution levels.

3.2. Concentrations of urinary metals among e-waste and office workers

We excluded six metals (i.e., Cr, Fe, Ga, Se, Hg, and U) from further analysis due to their detection rates falling below the 70 % threshold. Table 2 summarizes the concentrations (unit: µg/g creatinine) of each targeted chemical across different populations. Among the remaining metals, most concentrations in e-waste workers were higher than those in office workers, except for V (office workers: 0.39 vs. e-waste workers: 0.27, $p < 0.05$) and As. Furthermore, eight metals exhibited significantly higher median concentrations in e-waste workers ($p < 0.05$), including Li (25.09 vs. 33.36), Mn (1.78 vs. 4.15), Ni (2.10 vs. 2.77), Cu (5.81 vs. 9.23), Zn (404.35 vs. 431.52), Sr (151.33 vs. 186.26), Tl (0.35 vs. 0.43), and Pb (0.69 vs. 1.16). No statistically significant difference was observed in the 8-OhdG level between e-waste and office workers. When comparing the urinary levels of analytes in e-waste workers in other studies (Table 3), the internal exposure levels of metals in this study generally fell between the results reported from the developed countries (i.e., Sweden, Germany, and others) and those from developing countries (i.e., Ghana, Thailand, and others).

Table 1
Selected sociodemographic characteristics among e-waste and office workers.

n (%)	Office workers (n=100)	E-waste workers (n=101)	p*
Age (Mean ± SD)	47.8 ± 11.6	48.4 ± 11.4	0.691
Sex (Male)	53 (53.0)	58 (57.4)	0.681
With smoking cigarette habits	9 (9.0)	25 (24.8)	**0.003**
With alcohol drinking habits	25 (25.0)	20 (19.8)	0.557
Education levels below middle school	27 (27.0)	83 (82.2)	**< 0.001**
Marital status (Married)	54 (54.0)	73 (72.3)	**0.014**
Monthly family income < 40,000	29 (29.6)	50 (55.6)	**< 0.001**
Higher levels of residential air pollution	47 (51.6)	61 (74.4)	**0.003**
Eating marine fish ≥ 1 time/week	67 (67.7)	56 (67.5)	0.998
Eating freshwater fish ≥ 1 time/week	41 (44.4)	37 (44.6)	0.780
Eating crustacean seafood ≥ 1 time/month	67 (67.7)	60 (72.3)	0.608
Eating meat and poultry ≥ 1 time/day	61 (61.6)	68 (67.3)	0.486
Eating bacon ≥1 time/month	42 (42.4)	43 (43.0)	0.989
Eating pickle ≥1 time/month	44 (44.4)	45 (44.6)	0.999

* p-value for the difference between e-waste workers and office workers.

We compared the levels of metals among e-waste workers with different occupational characteristics (Supplementary Table 2). Notably, workers not involved in dismantling or repairing e-waste had higher concentrations of V, Mn, and Ba. Additionally, those employed by government-funded, larger enterprises also demonstrated elevated levels of V. In a further analysis of sociodemographic variations (Supplementary Table 3), workers with an education level of middle school or below displayed increased urinary metal concentrations, specifically Li, Mn, Cu, Sr, Cs, Tl, and Pb, compared to their more educated counterparts.

3.3. Composition profiles and correlations among metals in e-waste and office workers

The composition profiles for the metals in the urine samples of e-waste and office workers were calculated based on the median concentration of each metal (Supplementary Fig. 1). The profiles were found to be similar across both groups, with the primary metals identified as Sr, Zn, Rb, As, Li, Cs, Cu, and Ba. These metals collectively accounted for 99.53 % and 99.65 % of the total concentrations in the urine of e-waste and office workers, respectively.

The correlations among metals in e-waste and office workers are depicted in Supplementary Fig. 2. For the e-waste workers, significant statistical correlations were noted for Cs-Tl and Cs-Rb pairs, with coefficients of 0.74 and 0.76, respectively, both surpassing the threshold of 0.7. In the office workers, coefficients greater than 0.7 were noted for Tl-Rb (0.77), Cs-Rb (0.80), and Cs-Tl (0.74). The identification of the same pairs (i.e., Cs-Tl and Cs-Rb) in both e-waste and office workers suggests that the exposure sources of these metals (Cs, Tl, Rb) may be similar, indicating that they are not exclusively linked to workplace exposure.

3.4. Relationships between metals and 8-OhdG

The relationships between individual metals and 8-OhdG levels were measured by multiple linear regression (Table 4). Four metals were associated with the elevated oxidative stress levels in the models adjusted for age and sex, including Li (16.18, 95 %CI: 2.02, 30.99), Sr

Table 2

Urinary concentrations of chemicals among e-waste and office workers.

μg/g creatinine	Office workers (n=100)			E-waste workers (n=101)			*p*[*]
	Median	IQR	Detection rate (%)	Median	IQR	Detection rate (%)	
Li	25.09	21.05	100.0	33.36	21.50	100.0	**0.002**
V	0.39	0.53	78.0	0.27	0.51	69.3	**0.038**
Mn	1.78	6.38	63.0	4.15	8.08	92.1	**< 0.001**
Co	0.30	0.49	91.0	0.32	0.37	96.0	0.204
Ni	2.10	2.77	84.0	2.77	2.49	90.1	**0.047**
Cu	5.81	9.21	77.0	9.23	9.47	89.1	**0.002**
Zn	404.35	386.14	98.0	431.52	531.97	100.0	**0.017**
As	59.18	77.61	100.0	44.41	71.36	100.0	0.517
Rb	1063.3	970.07	100.0	1273.0	854.60	100.0	0.119
Sr	151.33	112.80	100.0	186.26	140.76	100.0	**0.016**
Cd	0.37	0.48	89.0	0.49	0.67	89.1	0.051
Cs	9.08	6.45	100.0	10.53	5.46	100.0	0.069
Ba	3.87	5.64	75.0	4.31	5.03	81.2	0.216
Tl	0.35	0.24	100.0	0.43	0.29	100.0	**0.015**
Pb	0.69	1.52	67.0	1.16	2.19	88.1	**< 0.001**
8-OHdG	4.19	2.18	100.0	3.82	2.78	100.0	0.596

Abbreviations: IQR, interquartile range.

[*] *p* for the difference between e-waste workers and office workers.

(22.14, 95 %CI: 7.25, 37.71), Cs (19.72, 95 %CI: 2.02, 40.49), and Tl (27.12, 95 %CI: 10.52, 47.70). However, no significant association was found in models further adjusting for other potential confounders (Model 2) and mutually adjusted for all metals (Model 3).

After examining the effects of individual metals, we employed the QGC model to investigate the overall impact of the metal mixture on oxidative stress (Table 5 and Fig. 1). The results indicated that the metal mixture significantly increased the 8-OHdG level (1.11, 95 %CI: 0.04, 2.19), with the positive partial effect (sum coefficients: 2.49) attributed to Mn (weight: 0.182) and Cd (weight: 0.182).

4. Discussion

This study is the first to measure the levels of various metals in the urinary samples of e-waste workers in Hong Kong, revealing significantly elevated internal exposure levels of metals among local e-waste workers, which could be associated with e-waste recycling activities. Additionally, this study found that both e-waste workers and office workers had similar composition profiles and likely shared common exposure sources of certain metals (i.e., Cs, Tl, Rb). Although the levels of 8-OHdG did not significantly differ between the e-waste and office workers, this study did find marginally significant associations between the metal mixture and 8-OHdG levels.

Urine samples are commonly used as a non-invasive indicator to monitor the internal exposure levels of metals, as many metals are naturally excreted from the body through urine (Zhang et al., 2019). Therefore, this study measured urinary samples to determine the impact of e-waste recycling on internal metal exposure levels. Consistent with the studies in Sweden and Ghana, where e-waste workers had elevated concentrations of urinary Ni and Pb (Julander et al., 2014; Wittsiepe et al., 2017), our study similarly noticed elevated levels of these metals in e-waste workers. However, our study additionally detected elevated Li levels in e-waste workers, suggesting that the high levels of Ni, Pb, and Li in Hong Kong, which likely stem from battery recycling, as these metals are the essential components of various types of batteries (Zhang et al., 2020).

When comparing the urinary metal concentrations from studies conducted in developing countries, such as Ghana, Pakistan, Thailand, Vietnam, Chile, and mainland China (Asante et al., 2012; Dartey et al., 2017; Kuntawee et al., 2020; Neitzel et al., 2020; Schecter et al., 2018; Seith et al., 2019; Shkembi et al., 2021; Srigboh et al., 2016; Tahir et al., 2021; Takyi et al., 2021, 2020; Wang et al., 2011a, 2011b), the levels of metals among the e-waste workers in Hong Kong were generally lower. This indicates that the exposure levels of these chemicals in Hong Kong's e-waste recycling sector were relatively low. Conversely, several analytes in this study exhibited higher concentrations than those observed in developed countries (Gerding et al., 2021; Gravel et al., 2023; Hanser et al., 2022; Julander et al., 2014). E-waste recycling practices vary significantly across countries and regions. In developing countries, e-waste is often handled by informal sectors using primitive methods, posing a significant chemical burden on the recycling workers (Orlins and Guan, 2016). In contrast, the relatively low internal exposure levels in Hong Kong may be attributed to the generally better occupational safety and health practices in the local e-waste recycling industry (Liao et al., 2024). Another possible explanation is that e-waste recycling in Hong Kong mainly focuses on dismantling e-waste and exporting the sorted components to other places for further processing (e.g., burning or acid leaching), which might cause heavier pollution (Liao et al., 2024). As the previous study has suggested, e-waste workers engaged in different job tasks experienced varying internal exposure levels (Takyi et al., 2021). Nevertheless, we found that the presumed high exposure group (i.e., those involved in dismantling or repairing e-waste) had lower levels of V, Mn, and Ba, which are trace elements susceptible to being substituted by other metals. Furthermore, our investigation into urinary metal levels across participants of different socioeconomic statuses revealed higher concentrations among less-educated individuals. This association can largely be attributed to the fact that the majority of less-educated participants (75.6 %) were employed in the e-waste industry in this study, where they experienced elevated internal exposure to metals.

Although e-waste workers generally exhibited higher concentrations of most tested metals, the composition profiles of both e-waste workers and office workers were found to be similar. This similarity suggests that while overall internal exposure levels to metals were elevated among e-waste workers, specific metals unique to e-waste recycling activities did not significantly alter the composition profile in this group. Correlation analysis further revealed that Cs, Tl, and Rb may share common sources of exposure, likely stemming from daily activities common to both e-waste and office workers in our study. These metals, which are naturally occurring but extensively released into the environment through anthropogenic activities (Karbowska, 2016; Melnikov and Zanoni, 2010; Usuda et al., 2014), are typically acquired through ingestion of contaminated food (such as vegetables, fruits, and animals) or water polluted by industrial sources (Anke and Angelow, 1995; Ghosh et al., 1993; Karbowska, 2016).

Next, we investigated the DNA oxidative damage index, 8-OHdG, and its relationships with metal exposure in our study. Despite the short half-life of 8-OHdG (i.e., 6–35 h) (Chen et al., 2020; Nguyen et al.,

Table 3
Comparison of the urinary concentrations of metals among e-waste workers in different countries or regions*.

Countries /regions	Publication year	Unit	Li	V	Mn	Co	Ni	Cu	Zn	As	Rb	Sr	Cd	Cs	Ba	Tl	Pb
This study (Hong Kong)	—	μg/g creatinine (Median)	33.36	0.27	4.15	0.32	2.77	9.23	431.52	44.41	1273	186.26	0.49	10.53	4.31	0.43	1.16
This study (Hong Kong)	—	μg/L (Median)	26.62	0.28	3.64	0.28	2.38	7.60	359.58	40.18	953.46	126.56	0.40	8.36	4.00	0.30	1.04
The levels in developing countries																	
China (Wang et al., 2011b)	2011	μg/g creatinine (Median)						**26**					**1**				**41**
Ghana (Takyi et al., 2021)	2021	μg/L (Median)					**9.07**			**43.90**	**1392.76**	**188.12**	0.38		**7.25**	**11.53**	**6.89**
Ghana (Asante et al., 2012)	2012	μg/L (Arithmetic mean)		**13**	**4.08**	**2.4**		**305**	**752**	**54.4**	**2090**	**142**	**0.43**	6.0	**5.9**	0.06	**7.30**
Ghana (Dartey et al., 2017)	2017	μg/g creatinine (geometric mean)		0.09		**0.61**	**2.9**	**13**	234	**101**							1.1
Thailand (Kuntawee et al., 2020)	2020	μg/g creatinine (Median)					**4.99**										
Thailand (Neitzel et al., 2020)	2020	μg/g creatinine (Mean)[a]			**15.08**								**0.68**				**7.49**
Vietnam (Schecter et al., 2018)	2018	μg/g creatinine (Median)								43.35			**0.99**				**3.22**
Thailand (Seith et al., 2019)	2019	μg/g creatinine (Mean)					**4.7**						**0.8**				**4.9**
Thailand (Shkembi et al., 2021)	2021	μg/g creatinine (Median)															**4.77**
Chile (Shkembi et al., 2021)	2021	μg/g creatinine (Median)															0.93
Ghana (Srigboh et al., 2016)	2014	μg/L (Mean)				**1.7**	**15.9**	**23.8**	**659**	**77.5**							**9**
Pakistan (Tahir et al., 2021)	2021	μg/g creatinine (Mean)					**22.94**	**63.94**	**734.95**	23.44			**2.78**				**13.19**
Ghana (Takyi et al., 2020)	2020	μg/L (Median)						**38.1**	**1044.4**								
China (Wang et al., 2011a)	2011	μg/L (Median)			2.45			3	0.31				**1.09**				**1.80**
The levels in developed countries																	
Sweden (Julander et al., 2014)	2014	μg/ L (Median)				0.25				13			0.37				**1.8**
Germany (Gerding et al., 2021)	2021	μg/L (Median)				**0.50**	0.50			3.0			0.08				
Canada (Gravel et al., 2023)	2023	μg/L (geometric mean)[b]				**0.32**	1.9			6.0							
France (Hanser et al., 2022)	2022	μg/L (Median)[c]	20		0.52	**0.67**	1.49						**0.92**				0.91

*Bold format means the concentration of the specific metal was higher than the corresponding metal in this study.

[a] The results were re-calculated from the results of the male and female workers in this study.

[b] The results from the "large" facility group with 33 workers.

[c] The samples consisted of administrative workers and e-waste workers.

Table 4
Relationship between log-transformed metals and log-transformed 8-OHdG in urinary samples *.

β (95 % CI)[a]	Model 1	Model 2	Model 3
Li	**16.18 (2.02, 30.99)**	12.76 (−3.63, 31.94)	5.92 (−13.76, 30.10)
V	3.05 (−1.01, 7.25)	2.70 (−2.15, 7.80)	4.01 (−1.71, 10.06)
Mn	1.01 (−2.02, 5.13)	0.40 (−3.63, 4.60)	−0.04 (−4.75, 4.90)
Co	−1.02 (−7.26, 5.12)	−2.47 (−8.90, 4.55)	−3.83 (−12.00, 5.41)
Ni	0.06 (−5.12, 5.13)	−0.07 (−6.06, 6.30)	−1.29 (−8.82, 6.91)
Cu	2.02 (−2.02, 6.18)	0.62 (−4.29, 5.78)	−0.17 (−6.61, 6.71)
Zn	2.02 (−4.08, 8.33)	−0.54 (−7.03, 6.40)	−3.83 (−12.53, 6.03)
As	6.18 (−4.08, 16.18)	0.31 (−11.03, 13.10)	−3.18 (−15.23, 10.80)
Rb	15.03 (−1.01, 32.31)	9.83 (−7.69, 30.67)	0.52 (−30.41, 45.18)
Sr	**22.14 (7.25, 37.71)**	13.69 (−2.97, 33.20)	12.07 (−10.64, 40.55)
Cd	3.05 (−2.02, 8.33)	2.10 (−3.95, 8.53)	2.61 (−4.62, 10.39)
Cs	**19.72 (2.02, 40.49)**	9.88 (−9.39, 33.25)	−10.08 (−37.88, 32.85)
Ba	1.01 (−3.05, 5.13)	0.01 (−4.73, 4.98)	−2.32 (−8.03, 3.86)
Tl	**27.12 (10.52, 47.70)**	18.26 (−0.67, 40.79)	19.99 (−10.49, 60.86)
Pb	2.02 (−1.01, 6.18)	2.20 (−2.13, 6.71)	4.13 (−1.50, 10.08)

Model 1 adjusted for sex and age.
Model 2 additionally adjusted for job types (i.e., e-waste or office workers), smoking habits, residential air pollution levels, and the frequency of eating marine fish based on Model 1.
Model 3 mutually adjusted for each metal based on Model 2.

[*] Both metals and 8-OHdG were log-transformed in the models, and the results were translated back; the bold font means statistical significance.

2014), metals, such as Pb (40 days) and Cd (three to four months), have relatively long half-lives in the blood (Ara and Usmani, 2015; Rahimzadeh et al., 2017). This suggests that metals could continuously stimulate the generation of 8-OHdG, which would not interfering with the assessment of health impacts (i.e., 8-OHdG levels) from metal exposure. While our fully adjusted linear regression model did not identify any metals significantly related to 8-OHdG levels, crude models adjusted for sex and age indicated that Li, Sr, Cs, and Tl were associated with increased 8-OHdG concentrations, with Tl exhibiting the largest effect size. Previous studies have highlighted Tl's potential to disrupt mitochondrial function and increase oxidative stress (Hanzel and Verstraeten, 2006; Zhang et al., 2022). Other studies even suggested that Tl may have higher toxicity compared to some traditional toxic metals, such as Hg, Cd, and Pb (Karbowska, 2016; Peter and Viraraghavan, 2005). However, such findings in our study diverged from previous studies conducted in populations residing near or within e-waste recycling sites (Kuang et al., 2022; Ni et al., 2014; Zhang et al., 2019). Details and discrepancies with these studies are summarized in Supplementary Table 4. For instance, Cu was found to be the most influential metal associated with 8-OHdG levels in urine samples from children and adults in e-waste recycling areas (Kuang et al., 2022), whereas urine levels of As, Hg, Cd, and Pb were highly correlated with 8-OHdG concentrations among residents in e-waste dismantling areas (Zhang et al., 2019). Additionally, Cd, Cr, and Ni were correlated with 8-OHdG in umbilical cord blood samples of neonates (Ni et al., 2014). These differences may arise from variations in sample types, sociodemographic characteristics, e-waste recycling methods, and other unexplored factors among these studies. Furthermore, we observed that the metal mixture marginally increased 8-OHdG levels, with Mn and Cd identified as primary contributors to oxidative DNA damage induction. A consistent overall effect of the metal mixture on 8-OHdG levels was noted among pregnant women in Wuhan, China, but Se was identified as the predominant contributor to oxidative stress (Zhang et al., 2022). The deviation in the results from single-pollutant and mixture models could be due to the chemical mixture, as a whole, having collinearity and complex interactions between individual chemicals, which could not be untangled in the single-pollutant models.

While this study has its own research merits, several limitations should be noted. Firstly, it only compared urinary metal concentrations between e-waste workers and office workers, using the latter as a reference. However, we did not measure environmental metal levels, particularly in food, which can accumulate metals through biological magnification. For example, rice has been identified as a major source of Cd exposure in e-waste dismantling areas (Fu et al., 2013; Zhang et al., 2019). Therefore, these unmeasured factors not only complicate the deduction of metal exposure pathways but also may distort associations between metal exposure and 8-OHdG due to unadjusted confounding factors. Secondly, this study collected only first-spot morning urine samples to measure metal levels. Although 24-hour urine collections are preferred, first-spot morning samples have been widely used in previous studies to mitigate the influence of water intake on chemical concentrations (Liu et al., 2022; Yang et al., 2020; Zhang et al., 2019, 2017). Additionally, first-spot morning samples enhance comparability across groups with different work shifts (e.g., multiple shifts for some e-waste workers versus one shift for office workers) and ensure participant's compliance with instructions. Thirdly, due to the challenges in recruiting e-waste workers, we faced difficulties in applying a sampling strategy, which also resulted in a smaller sample size of 101 e-waste workers. This limited sample size may have reduced statistical power to detect true differences in internal metal exposure levels between e-waste workers and reference groups. Lastly, this study was conducted during the COVID-19 pandemic, with workers wearing masks and increasing handwashing frequency at workplaces. These measures likely reduced metal absorption from various pathways, potentially underestimating the adverse health effects of e-waste recycling when using bio-sample monitoring. Nonetheless, the relatively low internal metal exposure levels observed may reflect effective workplace control measures implemented in the Hong Kong e-waste recycling industry.

5. Conclusion

This study reveals that the underprivileged e-waste workers in Hong Kong experienced elevated internal metal exposure levels from e-waste recycling activities, positioning their metal levels between those observed in e-waste workers from developing and developed regions. Among the chemicals tested, Cd and Mn emerged as critical metals in the mixture, which marginally caused DNA damage through oxidative stress. Given the relatively small scale of this study and the absence of an environmental monitoring matrix, future larger studies incorporating

Table 5
Effects of the internal metal mixture on urinary 8-OHdG levels.

Mixture effect [β (95 %CI)]*	Negative partial effect			Positive partial effect		
	Sum coefficients	First contributor and weight	Second contributor and weight	Sum coefficients	First contributor and weight	Second contributor and weight
1.12 (0.04, 2.19)	−1.37	As 0.385	Ba 0.299	2.49	Mn 0.182	Cd 0.182

[*] Adjusted for sex, age, job types (i.e., e-waste or office workers), smoking habits, residential air pollution levels, and the frequency of eating marine fish.

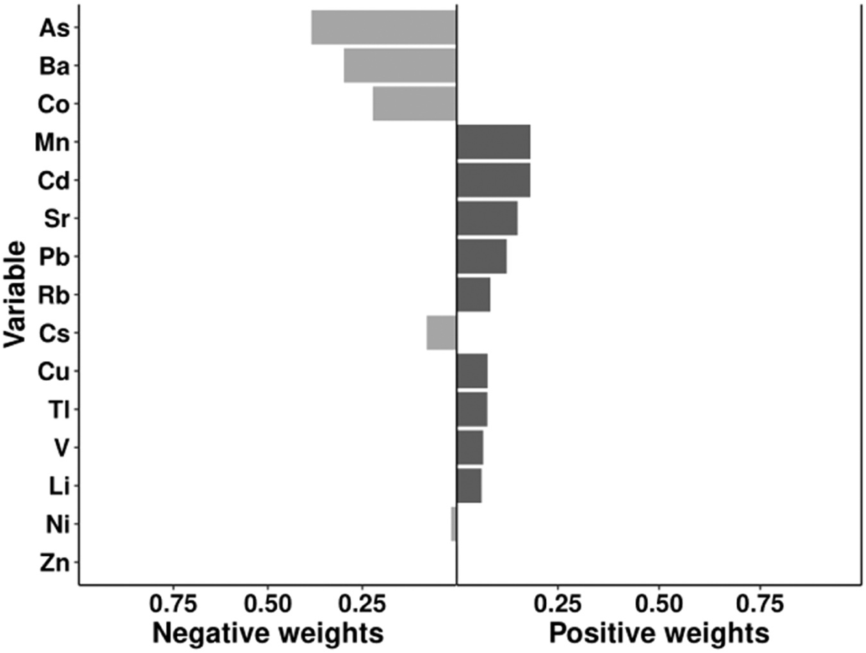

Fig. 1. Correlation between the metal mixture and 8-OHdG in urinary samples *. * Adjusted for sex, age, job types (i.e., e-waste or office workers), smoking and drinking habits, and residential air pollution levels.

environmental samples are warranted.

Funding

This work was supported by the Hong Kong Research Grants Council (General Research Fund no. 14604020 and no. 14609923; Collaborative Research Fund Grant no. C4023-20GF), lnt'I Tripartite Collaboration to Advance Exposome Research-Innovative Public Health Exposome Global Projects and Big Data Approach of the Chinese University of Hong Kong (Ref.: E.C./2017/006), and Research Committee of the Chinese University of Hong Kong (Postdoctoral Fellowship Scheme 2022–23, Ref.: WW/PDFS 2023/0664/23en; Strategic Seed Funding for Collaborative Research Scheme 2022–23, Ref.: TL/SSFCRS2223/0953/23ww). The study sponsor had no role in the study design, data collection, data analysis, decision to publish, preparation of the manuscript, or interpretation of the findings.

Data statement

Due to the sensitive nature of the questions asked in this study, survey respondents were assured raw data would remain confidential and would not be shared.

CRediT authorship contribution statement

Gengze Liao: Writing – original draft, Project administration, Investigation, Formal analysis, Conceptualization. **Xueqiong Weng:** Writing – review & editing, Software, Formal analysis. **Yanny Hoi Kuen Yu:** Writing – review & editing, Project administration, Methodology. **Feng Wang:** Writing – review & editing, Project administration, Funding acquisition. **Alan Hoi-shou Chan:** Writing – review & editing, Resources, Project administration, Conceptualization. **Victoria H. Arrandale:** Writing – review & editing, Funding acquisition, Conceptualization. **Lap Ah Tse:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization. **Shaoyou Lu:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

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

Data Availability

The authors do not have permission to share data.

Acknowledgments

We would like to thank the EcoTech Professional Association of Hong Kong and the Occupational Safety & Health Council, Hong Kong SAR, for their generous help in data collection.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2024.116872.

References

Ahamed, M., Siddiqui, M.K.J., 2007. Low level lead exposure and oxidative stress: current opinions. Clin. Chim. Acta 383, 57–64.

Anke, M., Angelow, L., 1995. Rubidium in the food chain. Fresenius J. Anal. Chem. 352, 236–239.

Ara, A., Usmani, J.A., 2015. Lead toxicity: a review. Inter. Toxicol. 8, 55–64.

Asante, K.A., et al., 2012. Multi-trace element levels and arsenic speciation in urine of e-waste recycling workers from Agbogbloshie, Accra in Ghana. Sci. Total Environ. 424, 63–73.

Chen, P., et al., 2018. Mechanisms and disease pathogenesis underlying metal-induced oxidative stress. Oxid. Med Cell Longev. 2018, 7612172.

Chen, P.-Y., et al., 2020. Associations between levels of urinary oxidative stress of 8-OHdG and risk of atopic diseases in children. Int J. Env Res Public Health 17, 8207.

Dartey, E., et al., 2017. Essential and non-essential trace elements among working populations in Ghana. J. Trace Elem. Med Biol. 44, 279–287.

Ding, Y., et al., 2019. Recovery of precious metals from electronic waste and spent catalysts: a review. Resour. Conserv Recy 141, 284–298.

Duc, H.N., et al., 2022. The effect of mixture of heavy metals on obesity in individuals≥ 50 years of age. Biol. Trace Elem. Res 200, 3554–3571.

Fu, J., et al., 2013. Influence of e-waste dismantling and its regulations: temporal trend, spatial distribution of heavy metals in rice grains, and its potential health risk. Environ. Sci. Technol. 47, 7437–7445.

Gerding, J., et al., 2021. Metal exposure of workers during recycling of electronic waste: a cross-sectional study in sheltered workshops in Germany. Int Arch. Occup. Environ. Health 94, 935–944.

Ghosh, A., et al., 1993. Effects of cesium on cellular systems. Biol. Trace Elem. Res 38, 165–203.

Gravel, S., et al., 2023. Occupational health and safety, metal exposures and multi-exposures health risk in Canadian electronic waste recycling facilities. Waste Manag. 165, 140–149.

Hanser, O., et al., 2022. Occupational exposure to metals among battery recyclers in France: biomonitoring and external dose measurements. Waste Manag. 150, 122–130.

Hanzel, C.E., Verstraeten, S.V., 2006. Thallium induces hydrogen peroxide generation by impairing mitochondrial function. Toxicol. Appl. Pharm. 216, 485–492.

Jomova, K., Valko, M., 2011. Advances in metal-induced oxidative stress and human disease. Toxicology 283, 65–87.

Julander, A., et al., 2014. Formal recycling of e-waste leads to increased exposure to toxic metals: an occupational exposure study from Sweden. Environ. Int 73, 243–251.

Karbowska, B., 2016. Presence of thallium in the environment: sources of contaminations, distribution and monitoring methods. Environ. Monit. Assess. 188, 1–19.

Keil, A.P., et al., 2020. A quantile-based g-computation approach to addressing the effects of exposure mixtures. Environ. Health Perspect. 128, 047004.

Kuang, H., et al., 2022. Four-year population exposure study: Implications for the effectiveness of e-waste control and biomarkers of e-waste pollution. Sci. Total Environ. 842, 156595.

Kuntawee, C., et al., 2020. Exposure to heavy metals in electronic waste recycling in Thailand. Int J. Env Res Public Health 17, 2996.

Liao, G., et al., 2024. Assessing neurobehavioral alterations among E-waste recycling workers in Hong Kong. Saf. Health Work-KR 15, 9–16.

Liu, X., et al., 2022. Urinary metals as influencing factors of coronary heart disease among a population in Guangzhou, China. Ecotoxicol. Environ. Saf. 241, 113746.

Lopes, A.C.B.A., et al., 2016. Lead exposure and oxidative stress: a systematic review. Rev. Environ. Contam. Toxicol. 236, 193–238.

Melnikov, P., Zanoni, L.Z., 2010. Clinical effects of cesium intake. Biol. Trace Elem. Res 135, 1–9.

Neitzel, R.L., et al., 2020. Metal levels, genetic instability, and renal markers in electronic waste workers in Thailand. Int J. Occup. Environ. Med 11, 72–84.

Nguyen, T.T.U., et al., 2014. Urinary 1-hydroxypyrene and 8-hydroxydeoxyguanosine Levels among Coke-oven Workers for 2 Consecutive Days. J. Occup. Health 56, 178–185.

Ni, W., et al., 2014. Associations of neonatal lead, cadmium, chromium and nickel co-exposure with DNA oxidative damage in an electronic waste recycling town. Sci. Total Environ. 472, 354–362.

Orlins, S., Guan, D., 2016. China's toxic informal e-waste recycling: local approaches to a global environmental problem. J. Clean. Prod. 114, 71–80.

Peter, A.J., Viraraghavan, T., 2005. Thallium: a review of public health and environmental concerns. Environ. Int 31, 493–501.

Rahimzadeh, M.R., et al., 2017. Cadmium toxicity and treatment: an update. Casp. J. Intern Med 8, 135–145.

Rautela, R., et al., 2021. E-waste management and its effects on the environment and human health. Sci. Total Environ. 773, 145623.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–191.

Schecter, A., et al., 2018. Biomonitoring of metals, polybrominated diphenyl ethers, polychlorinated biphenyls, and persistent pesticides in Vietnamese female electronic waste recyclers. J. Occup. Environ. Med 60, 191–197.

Seith, R., et al., 2019. Self-reported health and metal body burden in an electronic waste recycling community in Northeastern Thailand. J. Occup. Environ. Med 61, 905–909.

Shkembi, A., et al., 2021. Work task association with lead urine and blood concentrations in informal electronic waste recyclers in Thailand and Chile. Int J. Env Res Public Health 18, 10580.

Song, Q., Li, J., 2014a. Environmental effects of heavy metals derived from the e-waste recycling activities in China: A systematic review. Waste Manag. 34, 2587–2594.

Song, Q., Li, J., 2014b. A systematic review of the human body burden of e-waste exposure in China. Environ. Int 68, 82–93.

Song, Q., Li, J., 2015. A review on human health consequences of metals exposure to e-waste in China. Environ. Pollut. 196, 450–461.

Srigboh, R.K., et al., 2016. Multiple elemental exposures amongst workers at the Agbogbloshie electronic waste (e-waste) site in Ghana. Chemosphere 164, 68–74.

Tahir, M., et al., 2021. Heavy metal-associated oxidative stress and glutathione S-transferase polymorphisms among E-waste workers in Pakistan. Environ. Geochem Health 43, 4441–4458.

Takyi, S.A., et al., 2020. Micronutrient status of electronic waste recyclers at Agbogbloshie, Ghana. Int J. Env Res Public Health 17, 9575.

Takyi, S.A., et al., 2021. Biomonitoring of metals in blood and urine of electronic waste (E-waste) recyclers at Agbogbloshie, Ghana. Chemosphere 280, 130677.

Textor, J., et al., 2016. Robust causal inference using directed acyclic graphs: the R package 'dagitty. Int J. Epidemiol. 45, 1887–1894.

The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. http://collections.unu.edu/eserv/UNU:7737/GEM_2020_def_july1.pdf, 2020 (accessed 25 July 2024).

Usuda, K., et al., 2014. Risk assessment visualization of rubidium compounds: comparison of renal and hepatic toxicities, in vivo. Biol. Trace Elem. Res 159, 263–268.

Wang, H., et al., 2011a. Urinary heavy metal levels and relevant factors among people exposed to e-waste dismantling. Environ. Int 37, 80–85.

Wang, Q., et al., 2011b. Increased levels of lead in the blood and frequencies of lymphocytic micronucleated binucleated cells among workers from an electronic-waste recycling site. J. Environ. Sci. Health A Tox Hazard Subst. Environ. Eng. 46, 669–676.

Widmer, R., et al., 2005. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25, 436–458.

Wittsiepe, J., et al., 2017. Pilot study on the internal exposure to heavy metals of informal-level electronic waste workers in Agbogbloshie, Accra, Ghana. Environ. Sci. Pollut. Res Int 24, 3097–3107.

Wong, N.W., 2018. Electronic waste governance under "one country, two systems": Hong Kong and mainland China. Int J. Env Res Public Health 15, 2347.

Wu, X., et al., 2023. Organophosphate ester exposure among Chinese waste incinerator workers: urinary levels, risk assessment and associations with oxidative stress. Sci. Total Environ. 854, 158808.

Yang, D., et al., 2020. Exposure to heavy metals and its association with DNA oxidative damage in municipal waste incinerator workers in Shenzhen, China. Chemosphere 250, 126289.

Zeng, X., et al., 2016. Heavy metals in PM2.5 and in blood, and children's respiratory symptoms and asthma from an e-waste recycling area. Environ. Pollut. 210, 346–353.

Zeng, X., et al., 2018. Urban mining of e-waste is becoming more cost-effective than virgin mining. Environ. Sci. Technol. 52, 4835–4841.

Zhang, X., et al., 2017. Reference levels and relationships of nine elements in first-spot morning urine and 24-h urine from 210 Chinese children. Int J. Hyg. Environ. Health 220, 227–234.

Zhang, T., et al., 2019. Heavy metals in human urine, foods and drinking water from an e-waste dismantling area: Identification of exposure sources and metal-induced health risk. Ecotoxicol. Environ. Saf. 169, 707–713.

Zhang, Y., et al., 2020. Removal of toxic heavy metal ions (Pb, Cr, Cu, Ni, Zn, Co, Hg, and Cd) from waste batteries or lithium cells using nanosized metal oxides: A review. J. Nanosci. Nanotechnol. 20, 7231–7254.

Zhang, M., et al., 2022. Individual and mixtures of metal exposures in associations with biomarkers of oxidative stress and global DNA methylation among pregnant women. Chemosphere 293, 133662.

Zhao, Y., et al., 2022. Association between organophosphorus flame retardants exposure and cognitive impairment among elderly population in southern China. Sci. Total Environ. 848, 157763.