Yale University
EliScholar – A Digital Platform for Scholarly Publishing at Yale

Public Health Theses
School of Public Health

January 2023

Informal Electrical And Electronics Waste Recycling And Its Health Impacts: Evidence From Developing Countries

Zhen Liu
zhen.liu.zl528@yale.edu

Follow this and additional works at: https://elischolar.library.yale.edu/ysphtdl

Recommended Citation
Liu, Zhen, "Informal Electrical And Electronics Waste Recycling And Its Health Impacts: Evidence From Developing Countries" (2023). *Public Health Theses*. 2296.
https://elischolar.library.yale.edu/ysphtdl/2296

This Open Access Thesis is brought to you for free and open access by the School of Public Health at EliScholar – A Digital Platform for Scholarly Publishing at Yale. It has been accepted for inclusion in Public Health Theses by an authorized administrator of EliScholar – A Digital Platform for Scholarly Publishing at Yale. For more information, please contact elischolar@yale.edu.

Informal Electrical and Electronics Waste Recycling and its Health Impacts: Evidence from Developing Countries

Name: Zhen Liu

Year Completed: 2023

Year Degree Awarded: 2023

Degree Awarded: Master of Public Health

Department: Environmental Health Sciences, School of Public Health

Advisor/Committee Chair: Yong Zhu

Committee Members: Julie Zimmerman

Abstract

E-waste informal recycling poses severe threats to the environment and public health. This review provides an update to the 2013 and 2021 reviews, which systematically assessed adverse human health impacts associated with e-waste exposure. For this review, e-waste population health studies published between Jan 29, 2020 and Feb 23, 2023 were included. Databases including PubMed, Web of Knowledge, PsycNET, CNKI, Wanfang Data were searched, and the languages were not limited to English. Of the 4097 identified records, 58 studies examined the association between e-waste exposure and health, and are original studies based on population health outcomes. Current studies consistently support the finding that e-waste workers and people living in the e-waste informal recycling areas have higher levels of toxic chemicals in their bodies. Many studies also reported that children and newborns were more vulnerable to the e-waste pollution, which can negatively impact their neural system, endocrine system, and organ functions. Additionally, studies found DNA damage, abnormal epigenetic changes, and elevated oxidative stress among exposed populations. The social economic environment such as low income, less education and low health literacy that e-waste workers experience poses additional health risks due to chemical exposure. In order to protect public health, there is an urgent need for e-waste policy, law, regulation and green chemistry innovations in developing countries.

Keyword: environmental health sciences; e-waste; health impacts; developing countries

Acknowledgement:

I would like to express my sincere gratitude to my thesis advisors Dr.Yong Zhu and Dr. Julie Zimmerman for their valuable insights and guidance. I would also like to thank my boyfriend, Rixin Zhu, my family and my friends for their generous support. This research opportunity is a rewarding exploration that I never expected and will always cherish.

Table of Contents:

List of Figures

List of Tables

Introduction

The terms “E-waste”, “electronic waste” and “Waste from Electrical and Electronic Equipment (WEEE)” are used to refer to discarded and nonfunctional electronics. E-waste is different from functional secondhand electrical and electronic equipment, also called “Used Electrical and Electronic Equipment (UEEE)”. E-waste can come from a large variety of products that have plugs or batteries, such as computers, phones, washing machines, air conditioners, lamps, cameras, and more. According to estimates, over 50 million tonnes of e-waste are generated globally each year, and this amount is projected to reach 120 million tonnes per year by 2050 (World Economic Forum, 2019). However in 2019, less than 20% of e-waste is properly recycled, and the majority of e-waste is informally recycled in an uncontrolled manner (Forti et al., 2020). Although informal recycling widely exists in many regions of the world, most activities are located in low- and middle-income countries. High volumes of e-waste have been shipped to Asia and Africa countries, including China, Pakistan, India, Vietnam, Ghana, Nigeria, where e-waste regulations are less restrictive (World Economic Forum, 2019). The proliferation of internet technology, the emergence of "smart cities" in both developed and developing countries, the constant evolution of personal electronic products, and the growing use of solar panels to tackle the climate crisis have all led to a surge in e-waste generation (Jon Hurdle, 2023). The soaring amount of e-waste has raised significant concerns, posing threats to public health and the environment, particularly in developing countries.

Informal recycling is often unregulated and fails to meet safety or national environmental standards, posing a threat to worker’s health and releasing toxic chemicals into the environment.

Primitive techniques such as dismantling, open burning, metal stripping, acid washing, dumping, etc., are commonly used to extract valuable components from e-waste (Chi et al., 2011). Current studies suggest that workers in the informal sectors usually lack protective equipment, such as gloves or masks, to shield them from exposure (Chi et al., 2011). For example, workers use their bare hands to dismantle large equipment, which often causes cuts and muscle discomfort (Acquah et al., 2021). Another common technique involves heating or burning cables and circuit boards to recover valuable metals like copper and melt unwanted plastic; this process can release toxic chemicals into the atmosphere and irritate workers' eyes and respiratory tracts during their works (K. Wang et al., 2020). After heating, the remaining part of circuit boards is washed by highly corrosive acids to extract gold, and the acid wastewater, along with other pollutants such as heavy metals, may be dumped into nearby rivers (K. Wang et al., 2020).

Unlike informal recycling, which is largely operated by family workshops, formal recycling is typically conducted by large companies that are more centralized, regulated and controlled. These companies generally use similar processes as informal recycling but also use technologies to protect workers and prevent hazardous chemicals from being released into the environment (Johanna Treblin, 2013). Formal e-waste recycling can retrieve, recycle, and reuse valuable elements, which saves costs, reduces natural resource extractions and creates jobs. However, due to high costs, technology requirements and lack of regulations, formal recycling is uncommon in developing countries (Forti et al., 2020).

Informal e-waste recycling has been found to release numberous harzadous compounds such as heavy metals, phthalate esters (PAEs), dioxins and dioxin-like compounds (i.e., polychlorinated dioxins, PCDDs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), and others into the environment. Workers and nearby residents can be exposed to a mixture of these hazards through different exposure routes. For example, when e-waste workers collect and dismantle the e-waste by their bare hands, they can be exposed to toxic chemicals directly through dermal contact and dust ingestion (Tang et al., 2023) (Lebbie et al., 2021) (Zhao et al., 2022). they can also inhale hazards when heating cables and melting plastics from circuit boards (Lebbie et al., 2021). Additionally, toxic chemicals can be ingested through indoor and outdoor dust, as well as hand-to-mouth behaviors (Zhao et al., 2022). In addition, nearby residents can also be affected because many hazards can be released into and accumulate in the air, water, soil, and food system (Lebbie et al., 2021). A large amount of evidence shows that the soil, dust, water, and crop samples collected in e-waste dismantling areas contain several to hundreds times higher levels of persistent organic pollutants (POPs) and metals than in reference sites (W.-H. Zhang et al., 2012) (Qin et al., 2019) (Q. Wu et al., 2019). People who live near the recycling areas were also found to have significantly higher levels of toxicants in their blood than those who live far away from e-waste recycling sites (X. Zeng, Xu, et al., 2016) (Song et al., 2019) (Hashmi et al., 2022).

E-waste informal recycling can have a negative impact on human health. However, the associated adverse health effects depend on a variety of factors, and different individuals may have different health outcomes, even living in the same area. The time window of exposure (whether during pregnancy, early childhood, or adult life), e-waste recycling working history, living distance from polluted sites, and co-exposure from other pollutants, can all lead to different health consequences. For example, different types of e-waste recycling jobs can pose different levels of risks. A study found that smelting workers tend to be exposed to higher amounts of hazards than dismantlers and repairers, likely due to poor ventilation in working environments, and more toxicants can be released into the atmosphere by heating (Tahir et al., 2021). Behavioral factors also matter: children who wash their hands more frequently were exposed to lower levels of heavy metals (Xu et al., 2020), and different dietary habits can result in different PCBs exposure from food ingestion (Hashmi et al., 2022).

To comprehensively understand the health impacts of e-waste informal recycling, a systematic review of population health evidence of e-waste informal recycling was conducted in 2013 and 2021. In the first review, Grant et al. identified 23 studies from 2274 records published between Jan 1, 1965, and Dec 17, 2012 (Grant et al., 2013). In the second updated review, Parvez et al. examined 5645 records from Dec 18, 2012, to Jan 28, 2020 and identified 70 pieces of literature (Parvez et al., 2021). Both review articles found consistently and significantly higher levels of toxic chemicals exposure among exposed populations. They also found a consistent association between negative birth effects, DNA damage, cellular oxidative stress and immune function alterations with e-waste exposure (Grant et al., 2013) (Parvez et al., 2021). Based on the previous two systematic reviews, this current review examines articles since Jan 29, 2020, and provides new evidence of e-waste exposure and negative impacts in neuro system, endocrine system and organ function from more diversified countries.

Methods:

In this review, the selected studies should meet the following criteria: the study should examine the association between e-waste exposure and any human health outcomes including physical health, DNA damage or gene expression, neurodevelopmental health, mental health and behavioral health; the study was an original study; the study should focus on human population health outcomes. As a result, studies that focus on the effects in plants, animals, and in-vivo or in-vitro populations were excluded. Review articles, letters and commentaries that are not original studies were also excluded. The studies that only reported the exposure level but not the health outcomes were excluded as well.

This literature review searched five databases (PubMed, Web of Knowledge, PsycNET, CNKI, Wanfang Data) from Jan 29, 2020 to Feb 23, 2023 by using the following search terms: "(e-waste OR electronic waste OR WEEE) AND (health OR development OR mental OR education OR behavior OR learning OR psychological OR psychiatric* OR environment* OR exposure* OR food OR fish OR human breast milk; appendix)". The search terms are consistent with the search terms used in the previous systematic literature review published by Grant et al. and Parvez et al (Grant et al., 2013) (Parvez et al., 2021). Among five databases, CNKI and Wanfang Data are Chinese literature databases. In addition to the previous review that only included English literature, this search is not limited to English literature, but also includes literature written in Chinese, which has been translated to the English version in this paper. There are 4097 literatures identified in total through the initial database searching. After removing duplicates and literature that did not meet the above criteria, 58 papers were identified for this review. The most common reason for exclusion was not reporting the health effects.

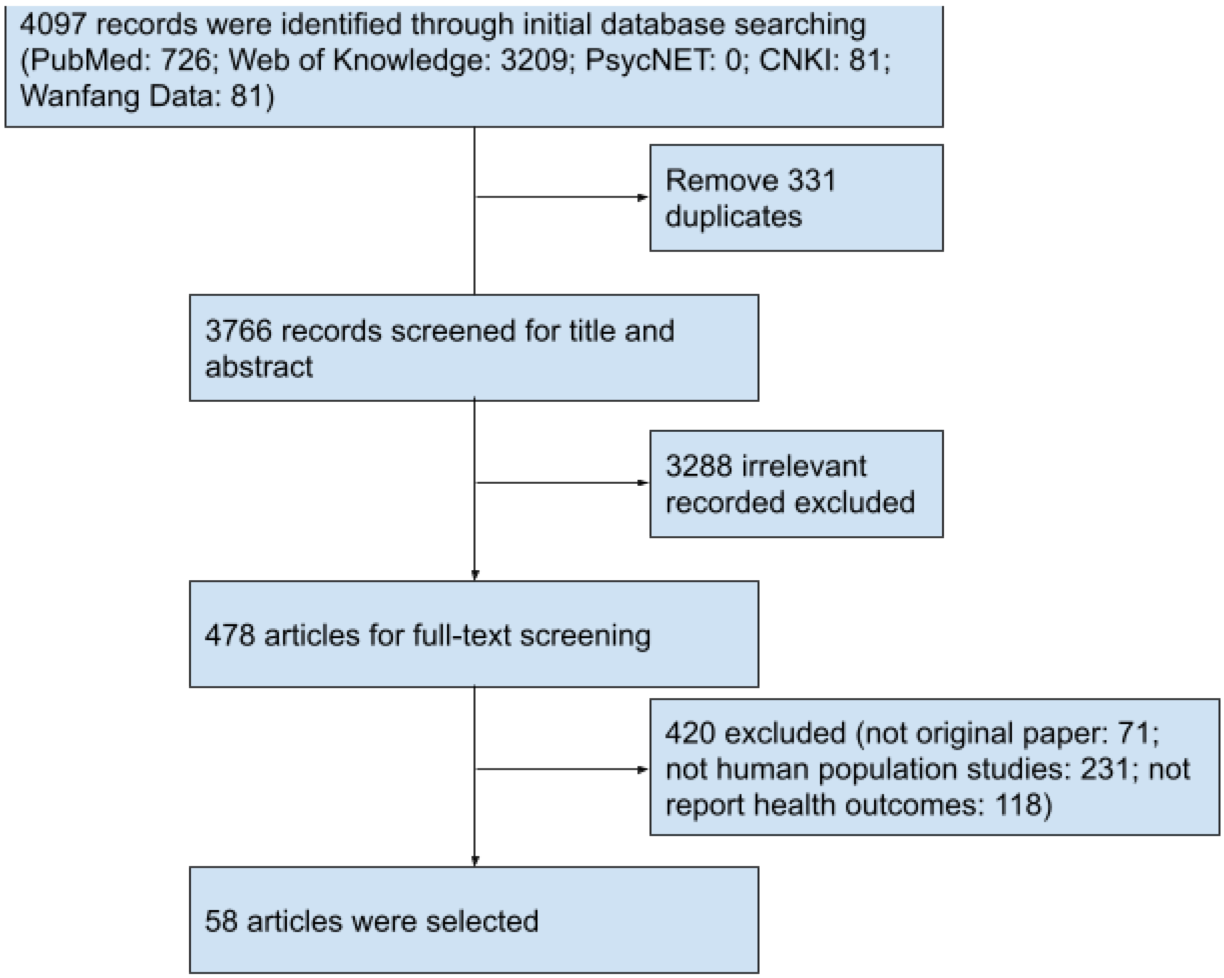

Figure 1: Study Selection Process

Results:

58 papers were identified after the full-text screening. For the selected literature, most of them are cross-sectional studies, with only three cohort studies. Among them, 57 were conducted in developing countries, with only one study in Canada. The majority of the reviewed articles were conducted in China (n=38), and Africa, including Ghana (n=12), Benin (n=1), Nigeria (n=1),

West Africa (n=1), followed by Thailand (n=1), Indonesia (n=1), India (n=1), Philippines (n=1), Vietnam (n=1), Pakistan (n=1), Canada (n=1). Compared to the previous two reviews in 2013 and 2021, which included over 90% of literature from China, there was a significant increase in the literature published in Africa, especially Ghana, in recent years. In all studies conducted in Ghana, all of them focus on Agbogbloshie, which has become the largest e-waste informal recycling site in Africa (Peter Yeung, 2019). In addition, most studies collected and compared data from both exposed and reference sites, while seven studies only collected data from exposed sites.

Several chemical exposures that are associated with e-waste informal recycling were identified, including metals (As, Pb, Cd, Cr, Mn, Co, Ni, Hg, Sn, Cu, Zn, Fe, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Lu, Ti, Ge, Rb, Mo, Sb, Ba, Pt, Cs, Ca, K, Na, Tb, Ho, Er and Y), polycyclic aromatic hydrocarbons (PAHs), polybrominated biphenyls (PBDEs), polychlorinated biphenyls (PCBs), dechlorane plus (DP), dioxins (PCDDs, PCDFs, and PCDDs/DFs), new flame retardants (NFR), organophosphate ester (OPE), SO_2, NO_2, O_3, CO and VOCs. Particle matters such as $PM_{2.5}$ and PM_{10} and physical hazards such as noise and cuts were also included. Different from the previous two reviews in 2013 and 2021, the studies included in this review focused less on PCBs, more on dioxins and NFRs as major toxicants. More recent studies also investigate health impacts from rare earth elements instead of traditional heavy metals such as Pb, Cd, Mn, Ni and Cr. Several recent studies from this review but none of the literature from the two previous reviews focused on physical hazards such as noise and cuts, musculoskeletal discomfort, or mental health such as stress. In general, most studies found the exposed groups had significantly higher levels of metals and POPs in their bodies than control groups. Moreover, except for two studies, the majority of the literature in this review found significant associations between e-waste exposure and negative health outcomes.

Growth and neurodevelopmental effects:

There were seven studies that investigated growth and developmental effects of e-waste exposure on newborns and children, four of them focused on newborn growth indicators and three focused on neurodevelopment. All of these studies found that pregnant women who live near to the e-waste recycling areas were more likely to bear higher levels of pollutants in their bodies; and their children were more likely to have poorer birth or neurodevelopmental outcomes. For effects on growth indicators, all four studies found negative impacts on birth head circumferences: Huang et al., found that pregnant women who live near to the e-waste sites had significantly higher urinary PAHs; they also found higher urinary PAHs levels were associated with smaller head circumferences and higher gestational age, but not with birth length, birth BMI, AGD and Apgar scores (Huang et al., 2020). Kim et al., found elevated levels of Pb, Cd, Cr and lower levels of Mn in exposed pregnant women; and their children were more likely to have smaller head circumferences, lower BMI, lower Ponderal index but no difference in birth weight (Kim et al., 2020). Moreover, significant negative association between PBDE exposure and PM exposure with birth head circumferences were also found (Y. Wang et al., 2022) (Z. Zeng, Xu, Wang, et al., 2022).

Different from growth indicators studies that measured varied toxicants, neuro-behavioral studies were mostly focused on heavy metals as major toxicants. In general, children who lived in e-waste recycling areas showed higher levels of Pb and Hg in their blood or hair than unexposed children. Children who had higher levels of Pb and Hg in their blood or hair were more likely to score lower in attention and academic performance and behavioral symptoms (Soetrisno & Delgado-Saborit, 2020) (X. Zeng et al., 2021). One study investigated the neural-behavioral impacts of air pollutants as a mixture of hazards (including $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and CO), and found significant associations between air pollution due to e-waste recycling activities and more emotional symptoms, more hyperactivity-inattention, more total difficulties and less prosocial behavior, but not with conduct problems or peer relationship problems (X. Zeng, Xu, Xu, et al., 2022).

	Study Design	**Exposed Population**	**Major Toxicants**	**Health Impacts**
Growth indicators:				
(Huang et al., 2020)	Cross sectional: exposed vs unexposed, China	163 pregnant women: exposed (n=100), unexposed (n=63)	PAHs	8 out of 10 OH-PAHs were significantly higher in the exposed group than in control (except 1-OHPhe and 1-OHPyr) Positive association between birth weight and PAHs: 2-OHFlu ($rs = 0.182$, $P < 0.05$). Negative association between head circumference and urinary PAHs level: 9-OHFlu ($rs = -0.174$), 3-OHPhe($rs = -0.176$), 9-OHPhe ($rs = -0.233$), and ΣOHFlu ($rs = -0.178$) were found. Positive association between gestational age and PAHs: 1-OHNap($rs = 0.183$), 2-OHFlu($rs = 0.175$), 3-OHPhe($rs = 0.167$), and ΣOHNap($rs = 0.170$). No significant correlations between OH-PAHs and birth length, birth BMI, AGD, and Apgar score were found. No significant associations between ΣOHPAH level and all birth outcomes were found
(Kim et	Cross sectional:	Pregnant	Pb, Cd, Cr,	Exposed mothers showed higher

al., 2020)	exposed vs unexposed, China	women: exposed (n=314) vs unexposed (n=320)	and Mn	concentrations of Pb, Cd, and Cr and lower Mn concentrations in blood. Exposed newborns had smaller head circumference (β −1.96 cm, 95% CI −2.39, −1.52), lower BMI (β −0.77 kg/m2, 95% CI −1.03, −0.51), and lower Ponderal Index (adj β −2.01 kg/m3, 95% CI −2.54, −1.47). No significant birth weight difference in two groups.
(Y. Wang et al., 2022)	Cross sectional: exposed vs unexposed, China	Pregnant women: exposed (n=100), unexposed (n=100)	PBDEs	All PBDE congeners and ∑BDEs were significantly higher in exposed group. Mean ∑BDEs level: 7.05 ng/g lw vs 0.84 ng/g lw Significant negative association observed between head circumferences with BDE-15 (β=-0.29), BDE-28 (β=-0.43), BDE-47 (β=-0.34), BDE-153 (β=-0.25), BDE-207 (β=-0.18), ∑BDEs (β=-0.24) Significant negative association observed between Apgar score (1 min) with BDE-15 (β=-0.32), BDE-28 (β=-0.24), BDE-183 (β=-0.2), BDE-207 (β=-0.22)
(Z. Zeng, Xu, Wang, et al., 2022)	Cross sectional: exposed vs reference group, China	Pregnant women: 101 exposed vs 103 unexposed	$PM_{2.5}$	Negative association between maternal PM2.5 exposure and newborn birth head circumference (β=-1.93, p=0.05)
Neuro-developmental and behavioral:				
(Soetrisno & Delgado-Saborit, 2020)	Cross sectional: exposed children vs unexposed, Indonesia	Children aged 6-9: exposed (n=22) vs unexposed (n=22)	Mn, Pb, Hg, As and Cd	Heavy metals level in hair: Pb: 0.155 mg/g vs 0.0729 mg/g (p=0.042); Hg: 0.008 mg/g vs 0.002 mg/g (p=0.021); no significant difference in Mn, Cd and As Attention and academic performance: TMT A (60.96 vs 38.64, p=0.001); TMT B (62.23 vs 44.5, p<0.00001); no significant difference in school subjects scores except sports (81.8 vs 75.3, p<0.00001) and arts (80.0 vs 75.7, p<0.00001); Significant association observed between hair Mn

				level and TMT_A (β=66, p=0.05) and TMT_B (β=105, p=0.033)
(X. Zeng et al., 2021)	Cross sectional: exposed vs unexposed, China	Preschool children (age 3-7): exposed (n=112), unexposed (n=101)	Pb	Blood Pb level: 5.19ug/dL vs 3.42ug/dL ($p<0.001$) Behavioral symptom score: total: 3 vs 2($p<0.001$); boys: 2.5 vs 2 ($p<0.001$); girls: 5 vs 2($p<0.001$) Negative association between blood Pb levels and NPY (β= −0.167, $p < 0.05$); no significant association between blood Pb with SP or dopamine. Positive association between blood Pb and behavioral problems (OR= 3.543; 95% CI 1.705 to 7.363)
(X. Zeng, Xu, Xu, et al., 2022)	Retrospective cohort study: exposed vs unexposed, China	Preschool children (age 3-7): exposed (n=112), unexposed (n=101)	$PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and CO	Positive association between average daily exposure dose of air pollution and emotional symptoms [OR (95% CI): 18.15 (2.72, 121.06)], hyperactivity-inattention [13.64 (2.28, 81.65)], total difficulties [8.90 (1.60, 49.35)] and prosocial behavior [− 7.32 (−44.37, −1.21)]. No association between average daily exposure dose of air pollution with conduct problems or peer relationship problems.
PAHs - Polycyclic aromatic hydrocarbons; 2(9)-OHFlu - 2(9)-hydroxyfluorene; 3-OHPhe - 3-hydroxyphenanthrene; ΣOHFlu - total 2-OHFlu and 9-OHFlu; BMI - Body mass index; AGD - Anogenital Distance; PBDEs - Polybrominated diphenyl ethers; TMT - Trail Making Test (TMT_A - attention domain; TMT_B - executive function domain); NPY - serum Neuropeptide Y; SP - substance P				
Table 1: E-waste Exposure and Growth and Neurodevelopmental effects				

Immunological and Hormonal:

Four studies investigated the immunological impacts associated with e-waste exposure among preschoolers and all of them found negative impacts on immune functions among e-waste exposed groups. Higher urinary PAHs levels in exposed groups were observed which were associated with higher levels of sialyl Lewis A, more lymphocytes and monocytes, less CD4+ T cells and higher risk of diarrhea (G. Chen et al., 2021). This study also found that exposed children were more likely to have gut-mucosal inflammation and develop adaptive immune responses to mediate the inflammation (G. Chen et al., 2021) . Cheng et al also found elevated urinary PAHs levels among exposed children; and they found positive associations between urinary PAHs and serum cytokines , NLRP3 and AhR gene expression, indicating the PAHs may affect cytokines release by mediating the gene expression (Cheng et al., 2020). In a study about e-waste exposure and asthma immunomodulation among children, higher Pb exposure was found to be associated with lower IL-13 expression, which may result in higher asthma risks among rs20541 gene carriers (Z. Zeng, Xu, Zhu, et al., 2022). One study also found that preschoolers who were exposed to e-waste were more likely to have lower white blood cells, neutrophil, monocyte, and lymphocyte; while no significant differences were found regarding eosinophils or basophils (Z. Chen et al., 2021).

Among ten studies that investigate the hormonal effects of e-waste exposure, four of these studies focus on sex hormones, five of them focused on thyroid hormones and one focused on growth hormones. Among the sex hormone studies, three measured dioxins as the major toxicants, and one study measured PAHs. All these studies found higher dioxins and PAHs levels were associated with lower sex hormone levels though the results on specific hormone types remain inconsistent. In addition, males were more affected by e-waste exposure on sex hormones than females. One study found a negative association between 3 dioxins levels and testosterone levels but not with DHEA (dehydroepiandrosterone), A-dione, or progesterone levels in boys, while no association between dioxins and sex hormones except progesterone was found in girls (Dong et al., 2020). Other studies also found negative association between 4 dioxins levels and

DHEA, as well as positive association between dioxins and A-dione (Androstenedione) (Z. Wang, Sun, et al., 2022) (Shi et al., 2020). In terms of PAHs exposure, there is one study that found higher urinary PAHs levels during pregnancy were associated with lower serum estradiol levels and testosterone levels in newborns, while no significant associations were found with serum anti-Müllerian level.

In general, five studies about thyroid hormones showed an association between e-waste exposure and impaired thyroid function. One study in formal e-waste recycling settings found negative associations between organophosphate ester (OPE) and total T, free T and free T/estradiol ratio but positive association between OPE and total T4 among male workers; while in female workers, negative association were only found between OPE and free T3 levels (Gravel et al., 2020). One study found a negative association between Fe blood level and TSH in females (C. Guo et al., 2021); while another study found positive association between La and Ce blood levels with TSH levels (C. Guo et al., 2020). Other studies also found negative association between PCBs, PBDEs, NFRs and PM2.5 exposure with TSH levels (L. C. Guo et al., 2020) (Z. Zeng, Xu, Wang, et al., 2022). No significant associations were found between urinary PCBs, PBDEs, NFRs levels with other thyroid hormones including T3, T4, FT3, FT4, TBG, TSH, TRα, TRβ (L. C. Guo et al., 2020). In addition, no significant associations were found between PM2.5 exposure and neonatal TSH, FT3 or FT4 levels (Z. Zeng, Xu, Wang, et al., 2022). Only one study investigated the HPA-axis hormone effects by e-waste exposure and found positive associations between blood Cr and Ni levels with ACTH, CRH and cortisol (Li, Li, et al., 2020). Two studies also investigate the mechanistic relationship and found the MDA and 8-iso-PG can play an important role in mediating the effects of elevated heavy metals levels on hormones (C. Guo et al., 2021) (Li, Li, et al., 2020).

	Study Design	**Exposed Population**	**Major Toxicants**	**Health Impacts**
Immunological:				
(G. Chen et al., 2021)	Cross sectional: exposed vs unexposed, China	Pre-school children (2-7 years): exposed group (n = 119) vs reference group (n = 113)	PAHs	Higher urinary PAHs metabolites level in exposed group (except 9-OHFlu, 2-OHPhe, 3-OHPhe, and 9-OHPhe) Exposed group had higher SLA level, more lymphocytes and monocytes, less CD4+ T cells, and a higher risk of diarrhea than the unexposed group.
(Cheng et al., 2020)	Cross sectional: exposed vs unexposed, China	Preschoolers: exposed (n=121) vs unexposed (n=127)	PAHs	Urinary ΣOH-PAHs concentration: 26.42 μg/g Cre vs 15.67 μg/g Cre, $p < 0.001$ Positive association between urinary ΣOH-PAHs concentration and serum cytokines (IL-1β, IL-18, IFN-γ, and TNF-β) , which were partially mediated by NLRP3 expression(37.9%, 38.0%, 35.9%, and 258.6%, all $p < 0.05$); Positive association between urinary ΣOH-PAHs concentration and serum cytokines (TNF-α, IL-4, IL-10, IL-12p70, IL-22, and IL-23) which were mediated by AhR (15.2%, 22.0%, 24.0%, 29.9%, 27.4%, and 24.0%, all $p < 0.05$)
(Z. Zeng, Xu, Zhu, et al., 2022)	Cross sectional study: exposed children vs unexposed, China	155 pre-school (3-7 years) children: 75 exposed vs 80 unexposed	Pb and Cd	Blood Pb: 5.89 vs 3.35 μg/dL ($p<0.05$); Urinary Cd: 6.04 vs 1.82 μg/g ($p < 0.05$); IL-13: 3.674 vs 4.410 ng/L ($p< 0.01$); no significant difference between IL-10 High blood Pb level is associated with low IL-13 expression among rs20541 carriers (OR = 5.37, 95% CI: 1.96, 14.73) and rs1800925 carriers (OR = 8.45, 95% CI:

				2.61, 27.32)
(Z. Chen et al., 2021)	Cross sectional: exposed children vs reference children, China	Pre-school children (age 3-7) 319 exposed vs 176 unexposed	Pb	Blood Pb level: 4.51 ug/dL vs 3.98 ug/dL ($p<0.001$) White blood cells: 7.49×10^9/L vs 6.59×10^9/L ($p < 0.001$); neutrophil: 3.28×10^9/L vs $2.96x10^9$/L ($p<0.01$); monocyte: 0.47×10^9/L vs 0.37×10^9/L ($p<0.001$), and lymphocyte: 3.28×10^9/L vs 2.86×10^9/L ($p<0.001$); no significant difference in Eosinophils or Basophils between two groups.
(Luo et al., 2021)	Cross sectional: exposed vs unexposed, China	187 pre-school children (age 3-6 years): exposed (n=82) vs unexposed (n=105)	Pb	Pb level: 4.11 ug/dL vs 4.49 ug/dL (p=0.01) Plasma endotoxin levels: 2.24 EU/mL vs. 1.85 EU/mL (p = 0.037). Positive association between Pb and plasma endotoxin (B (95% CI) = 0.072 (0.008, 0.137) Positive association between endotoxin with Ln-neutrophils(B (95% CI) = 0.054 (0.015, 0.093)), monocytes(B (95% CI) = 0.018 (0.005, 0.031)), and Ln-LTB4(B (95% CI) = 0.049 (0.011, 0.087))
(Y. Zhang et al., 2020)	Cross sectional: exposed vs unexposed, China	147 children (aged 3-7 years): exposed (n=73), unexposed (n=74)	Cd, Hg, Pb and As	Pb: 37.23 µg/L vs 22.74 µg/L; Cd: 0.33 µg/L vs 0.23 µg/L; Hg: 1.46 µg/L vs 1.10 µg/L; As: 5.91 µg/L vs 4.18 µg/L. (all $p < 0.001$) Positive association between neutrophil cell counts with Pb: β (95% CI)=0.196 (0.003, 0.394), Cd: β (95% CI)=0.117 (0.028, 0.263) , Hg: β (95% CI)=0.157 (0.002, 0.313); Positive association between monocyte cell number with Cd: β (95%)= 0.109 (0.009, 0.226); no significant association between As and neutrophil, or Pb, Hg and As with monocyte, or any heavy metals with lymphocyte. No significant associations between heavy metals exposures and 4 tested pro-inflammatory cytokines (IL-1β, IL-6, IL-8, TNF-α), except positive association

				between IL-6 level and Pb exposure: β (95% CI)= 0.327 (0.036, 0.617) No significant associations between heavy metals exposures and 4 tested anti-inflammatory cytokines (IL-1RA, IL-4, IL-10, IL-13) were found
(Zheng et al., 2021)	Cross sectional: exposed vs unexposed, China	324 children (aged 3-7 years): exposed (n=195), unexposed (n=129)	Pb and Cd	Pb: 5.70 μg/dL vs 3.53 μg/dL($p < 0.01$); Cd: 0.56 μg/L vs 0.47 μg/L ($p < 0.05$) Association between blood Pb levels and IFN-γ level (OR = 2.012, 95% CI: 1.063–3.809), IL-13 (OR = 0.523, 95% CI: 0.284–0.964) (both $P < 0.05$). Positive association between Cd levels and IgG1 (OR = 1.829, 95% CI: 1.006–3.327) ($p < 0.05$). No significant association between Pb with IgG1 or IgG2. No significant association between Cd with IFN-γ, IL-13 or IgG2. Significant mediating effects of IL-13 on the association between Pb and IgG1 (β=0.4385, $p<0.05$)
Hormonal (Sex hormone):				
(Dong et al., 2020)	Cross sectional: e-waste residents, China	50 pairs of breastfeeding mothers and their infants	dioxins	Total PCDDs, PCDFs, and PCDDs/DFs were 4.7 pg/lipid, 4.6 pg/lipid, and 9.7 pg/lipid Among boys: negative association between Testosterone levels and 3 out of 14 dioxins (2,3,7,8-TeCDD: β=−0.712, 95% CI:-1.465, -0.308; 1,2,3,7,8-PeCDD, β=−0.813, 95% CI:-1.658, -0.096; 1,2,3,4,7,8-HxCDF: β=−0.636, 95% CI: -1.059, -0.302); no association between dioxins with DHEA, A-dione, or progesterone. Among girls: no association between dioxins level and testosterone, DHEA, or A-dione, except the total PCDDs/DFs and Progesterone (β=−0.997, 95% CI: -6.945, -0.046)

(Z. Wang, Sun, et al., 2022)	Cross sectional: e-waste residents, China	42 pairs of breastfeeding mothers and their 6 years old child	dioxins	TEQ PCDDs, PCDFs, and PCDDs/DFs in blood level: 4.6, 4.7, and 9.7 pg/lipid, respectively. Negative association between DHEA levels with 4 out of 14 dioxins including 1,2,3,7,8-PeCDD (r=−0.328, p=0.034), 1,2,3,6,7,8-HxCDD (r=−0.312 , p=0.044), 2,3,4,7,8-PeCDF(r=−0.353, p=0.022), and 1,2,3,6,7,8-HxCDF(r=−0.346, p=0.025) No association between dioxin with A-dione or Progesterone, except negative association between 1,2,3,7,8-PeCDF and A-dione (r=−0.364, p=0.018).
(Shi et al., 2020)	Cross sectional: e-waste recycling area	76 adults males living in e-waste recycling area	dioxins	Comparing the < 25th percentile group, higher DHEA level in men with low PCDFs-TEQ level (3.80- 6.31 pg/g lipid) :1933 vs 1447 pg/ml, but not in medium and high groups; Higher DHEA level in low PCDD/PCDFs-TEQ group (8.57 -15.11 pg/g lipid): 1996 vs 1360 pg/ml, but not in medium and high groups. Higher A-dione in high PCDFs-TEQ group (≥ 11.34 pg/g lipd): 2404 vs 1848, but not in low or medium groups. Higher 3β-HSD concentrations in low- and high TCDD groups (TCDD=1.30–1.67 and ≥ 2.64 pg-TEQ/g lipid), but not in medium level group: 719 and 807 vs 496.
(Huang et al., 2020)	Cross sectional: exposed vs unexposed, China	163 pregnant women: exposed (n=100), unexposed (n=63)	PAHs	Exposure level: see details above Negative associations between E2 levels and PAHs (1-OHNap, 9-OHPhe, and ΣOHNap), and between T levels and PAHs (1-OHNap, 2-OHNap, 2-OHFlu, 9-OHFlu, 2-OHPhe, 3-OHPhe, 9-OHPhe, ΣOHNap, and ΣOHFlu). No significant association between OH-PAHs and serum AMH level.
Hormonal (Thyroid Hormone)				
(Gravel	Cross sectional: 6	100	Organophosph	No significant difference in PBDE

et al., 2020)	formal e-recycling companies vs 1 commercial (no e-waste) recycling company, Canada	workers: e-waste recycling (n=85) vs non e-waste workers (n=15)	ate ester (OPE), Hg, PBDE, Pb, Cd	congeners in plasma or OPE urinary metabolites except BDE209 (18 ng/g lipids vs.1.7 ng/g lipids) and DPhP (1.7 ng/ml vs. 0.95 ng/ml). Men: BDE209 twofold increase was associated with 3.1% higher levels of total T4 (β=3.1%, 95% CI: 0.07, 6.1); and a twofold increase in tb-DPhP was associated with 18% lower level of total T(β= -18% (−29, −4.7), 18% lower levels of free T(β=-18% (−27, −6.9) and 13% lower levels free T/estradiol ratio (β=-13% (−25, 0.70). Women: BDE153 twofold increase was associated with 10% lower levels of free T3 (β=-10% (−17, −3.2)). No significant associations between FRs and testosterone levels.
(C. Guo et al., 2021)	Cross sectional: exposed vs unexposed, China	Residents: exposed (n=87, 47 females) vs unexposed (n=81, 37 females)	Cu, Fe, Mn and Zn	Exposed group showed lower levels of Fe (0.473ug/L vs 0.495ug/L, $p=0.018$) and Mn (0.013 ug/L vs 0.014 ug/L, $p=0.025$). No significant difference in Cu and Zn TSH: 1.7 mU/L vs 1.48 mU/L, $p=0.001$. No significant difference in FT3 or FT4 In females: Negative association between TSH and Fe (β (95% CI): − 3.161 (−5.625, −0.696), $p = 0.013$). No association between other elements and thyroid hormones In females: Negative association between Fe with MDA (β (95% CI): − 29.503 (−51.983, −7.023), $p = 0.011$). No association between Cu, Mn or Zn with MDA or 8-iso-PG
(C. Guo et al., 2020)	Cross sectional: exposed vs unexposed, China	Residents: exposed (n=87) vs unexposed (n=81)	La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Lu	La blood level: 0.479ng/ml vs 0.032ng/ml ($p<0.001$); Ce: 2.546ng/ml vs 0.017ng/ml($p<0.001$); Pr: 0.020 ng/ml vs 0.011ng/ml ($p<0.001$). No significant difference in other elements TSH: 1.7 mU/L vs 1.48mU/L ($p = 0.002$); no significant difference in FT3, FT4 and TRH levels;

				Positive association between high level of La exposure (>0.538ng/ml) with TSH level (β: 0.305 (0.027, 0.584), p = 0.032) when compared to low La (<0.032ng/ml). Positive association between high level of Ce exposure (Q3:1.216–2.546 and Q4:>2.546) with TSH level (Q3: β : 0.279 (0.008, 0.55); Q4: β: 0.380 (0.107, 0.653)) when compared to low Ce (<0.011ng/ml). No significant difference between TSH level and low level of La or Ce
(L. C. Guo et al., 2020)	Cross sectional: exposed vs unexposed, China	114 Sixth-grade students: exposed (n=57) vs unexposed (n=57)	PCBs, PBDEs, NFRs	PCBs: 380 ng g lipid−1 vs 300 ng g lipid−1; PBDEs: 330 vs 150; NFR: 430 vs 270, all p<0.05 Positive association between ID1 gene expression and levels of PCB-28, -101, -180, ΣPCB, BDE-153, -154, -183, -204, -207, -209, ΣPBDE, TBB, DPs, DPa, and ΣNFR; no monotonic associations observed between PCBs, PBDEs, NFRs and other TH related proteins and genes (T3, T4, FT3, FT4, TBG, TSH, TRα, TRβ) No significant difference in TH related proteins and genes between exposed and control group except TSH (2.2 vs 2.8nmol/L, p=0.01) and ID1 (4.2×10^{-3} vs 2.4×10^{-3}, $p=1 \times 10^{-7}$)
(Z. Zeng, Xu, Wang, et al., 2022)	Retrospective cohort study: exposed vs unexposed, China	Pregnant women: exposed (n=101), unexposed (n=103)	$PM_{2.5}$	Neonatal FT4 levels (pmol/L): 15.4 vs 13.97 (p=0.031); Birth head circumference (cm): 33.83 vs 35.29 (p<0.001) $PM_{2.5}$ individual chronic daily intake: 0.78 ± 0.10 mg/kg·day vs 0.52 ± 0.06 mg/kg·day (p < 0.001) Positive association between PM2.5 and BAI1 methylation (cg25614253: 8.00% vs 7.00%, p = 0.023; position +13: 83.00% vs 76.00%, p < 0.001; position +32: 70.00% vs 49.00%, p < 0.001), except no association in position −12 ; Positive association between PM2.5 and CTNNA2 methylation: cg20208879: 62.00% vs 64.00%, p=0.024, except no significant association in position +32

				No significant association between PM2.5 CDI and thyroid hormone except TSH in T2 (OR = 5.03, 95% CI: 1.00 to 25.20, p = 0.05)
(Z. Zeng, Xu, Wang, et al., 2022)	Cross sectional: exposed vs reference group, China	Pregnant women: 101 exposed vs 103 unexposed	$PM_{2.5}$	No significant associations found between maternal PM2.5 exposure and neonatal TSH, FT3 or FT4 levels
Hormone (HPA Axis)				
(Li, Li, et al., 2020)	Cross sectional: exposed vs unexposed, China	148 residents: exposed (n=68) vs unexposed (n=80)	Cr, As, Co, Ni, Ag, Se, Hg, La, Ce, Ti, Mn, Ge, Cd, Cu, Zn, Rb, Pb	9 of 17 metals were significantly higher in exposed group, including Cr, As, Co, Ni, Ag, Sn, Hg, La, Ce Exposed group: positive association between Cr and Ni with all HPA axis related hormones (ACTH, CRH and cortisol). Positive association between MDA and 8-I and 3 hormones. No significant association observed in other metals with hormones or in the unexposed group.
PAHs - Polycyclic aromatic hydrocarbons; SLA - sialyl Lewis A; Cre - Creatinine; IL - interleukin; IFN - interferon; NLRP3 - NLR family pyrin domain containing 3; AhR - aryl hydrocarbon receptor; TNF-α - Tumor necrosis factor alpha; DHEA - dehydroepiandrosterone; 3β-HSD - 3β-hydroxysteroid dehydrogenase; A-dione - Androstenedione; E2 - estradiol; T - testosterone; AMH - anti-Müllerian hormone; MDA - malondialdehyde; TSH - thyroid stimulating hormone; PCDD - Polychlorinated dibenzo-p-dioxins; PCDF - polychlorinated dibenzofurans; tb-DPhP - tert-butyl diphenyl phosphate; TH - thyroid hormone; HPA - Hypothalamic pituitary adrenal axis; ACTH - adrenocorticotropic hormone; CRH - Corticotropin releasing hormone				
Table 2: E-waste Exposure and Immunological and hormonal effects				

Genotoxicity and oxidative stress:

For DNA damage, six out of nine studies focused on metals exposure from e-waste, two of them investigated $PM_{2.5}$ and PM_{10} , while one study did not assess the specific toxicants. Pb, Cd, Cr, Ni and As were the most commonly assessed metals. Except for two studies conducted in Vietnamese children and Chinese children that did not find significant differences in blood Pb, Cr and Cd levels, and Cd levels separately, most of these studies did find significantly higher levels of blood metals in exposed groups than in unexposed groups across countries. Two studies that investigated the health effects with PM also found significantly elevated exposure of air pollutants per day among exposed e-waste workers in Ghana and pregnant women who lived near to the recycling sites in China.

All of these studies found some levels of significant differences in DNA damage or methylation levels associated with e-waste exposure. Among the six studies that measured Pb impacts, half of them found significant genetic impacts that were associated with Pb exposure: Alabi et al. found higher Pb level were positively associated with nuclear abnormalities including micronucleated and binucleated cell, cells with lobed nuclei, cell pyknosis and karyorrhexis among Nigerian teenagers (Alabi et al., 2020); Issah et al. found a negative correlation between Pb blood levels and LINE1 methylation among Ghana e-waste workers; and Xu et al. found higher Pb levels were associated with lower MeCP2 methylation level among Chinese preschoolers (Xu et al., 2020). Additionally, studies that tested other heavy metals also found elevated levels of Ni, As and Ce among exposed groups and were associated with DNA damage: Ngo et al. found children who had higher blood levels of As, Ni and Ce were more likely to have longer DNA tail length, which means more DNA damage (Ngo et al., 2021); in Li, Liu. et al.'s study, they found positive correlation between blood Ni levels and mitochondrial DNA copy number (MCN) among e-waste residents and former workers, as well as positive correlation between blood Ni levels and length of telomere in former workers in China (Li, Liu, et al., 2020); Alabi et al. also found positive correlation between blood Ni levels and nuclear abnormalities (Alabi et al., 2020); and Li, Guo et al. found negative association between blood As levels and 5-Methylcytosine levels among former workers, and negative association between blood Ce levels and 5-Methylcytosine levels among e-waste residents in China (Li, Guo, et al., 2020). Two studies that assessed the particulate matter exposure also found significant positive association between PM exposure and DNA methylation levels at CpG sites (Issah, Arko-Mensah, Rozek, Rentschler, et al., 2022) (Z. Zeng, Xu, Wang, et al., 2022).

There were seven studies that investigated the oxidative stress related to e-waste exposure: four of them focus on the metals, one focused on PAHs and one focused on both the metals and PAHs. Most of the studies found elevated levels of Pb, Ni, Co, Hg, Sn and PAHs levels among exposed groups, and no significant differences in Cu, Cr, Cd levels. Significantly lower levels of Zn in exposed groups was found in one study (Z. Wang, Xue, et al., 2022). Except for one study conducted in Thailand that did not find any significant oxidative stress differences related to e-waste exposure, five out of six studies found elevated levels of at least one oxidative stress biomarker among exposed groups than unexposed groups. Malondialdehyde (MDA) and 8-Hydroxy-2'-deoxyguanosine (8-OHdG) were the most commonly studied biomarkers of oxidative stress. Tahir et al. found elevated levels of MDA, Glutathione reductase activity and lower catalyst in e-waste workers than controls in Pakistan (Tahir et al., 2021). Kuang et al. found higher levels of metals, VOC metabolites and PAH metabolites were associated with higher levels of MDA and 8-OHdG among e-waste residents in China; they also found a significant decrease in 8-OHdG, but not in metals or MDA levels among the residents, after the informal recycling sites had been shut down for 4 years (Kuang et al., 2022). One study also found significant positive association between blood Ni levels with MDA (Z. Wang, Xue, et al., 2022). Moreover, positive associations between blood Co levels with oxidative stress indicators of blood-brain-barrier disturbance were also found (Li et al., 2021).

	Study design	**Exposed population**	**Major Toxicants**	**Health Impacts**
DNA Damage:				
(Alabi et al., 2020)	Cross sectional: exposed group v.s reference group, Nigeria	95 teenager e-waste scavengers v.s 104 unexposed teenagers	Pb, Ni, Cd, and Cr	Blood heavy metals level: Pb (38.34 µg/L vs 2.91µg/L, $p<0.01$); Cd (2.85 µg/L v.s 0.25 µg/L, $p<0.01$); Cr (4.22 µg/L v.s 0.04 µg/L, $p<0.05$); Ni (1.98 µg/L v.s 0.02 µg/L, $p<0.01$). DNA damage including micronuclei, lobed nuclei, pycnosis, karyorrhexis, and binucleated cells is significantly higher in the exposed group. Positive correlation between nuclear abnormalities and Pb (Rs = 0.27, $p = 0.001$), Cd (Rs = 0.20, $p = 0.001$), Cr (Rs = 0.25, $p = 0.002$), and Ni (Rs = 0.19, $p = 0.002$)
(Ngo et al., 2021)	Cross sectional: exposed villagers v.s unexposed villagers, Vietnam	80 children: exposed vs unexposed	Pb, Cd, Cr, Ni, As	Exposed children had significantly higher blood Ni and As levels. No significant differences in Pb, Cd and Cr Greater DNA damage in exposed children $p < 0.001$. Positive association between total blood metal levels and tail length ($r = 0.249$, $p < 0.05$)
(Issah et al., 2021) (Issah, Arko-Mensah, Rozek, Zarins, et al., 2022)	Cross sectional: exposed v.s reference group, Ghana	100 male e-waste workers vs 51 unexposed people	Pb, Zn, Cd	Blood heavy metal levels: Cd (0.59 µg/L v.s 0.81 µg/L, $p=0.003$), Pb (76.82 µg/L v.s 40.25 µg/L, $p<0.001$); urine levels: Cd (no significant difference), Pb (6.89 µg/L and 3.43 µg/L, $p \leq 0.001$). LINE1 methylation: no significant difference between 2 groups; significant negative association between blood Pb level and LINE1 methylation in control groups ($\beta BPb = -0.027$, 95% CI -0.045, -0.010, $p = 0.003$) but not in exposed

				group ($\beta BPb = -0.005$, 95% CI -0.011, 0.000, $p = 0.058$). Inverse correlation between Zn and Methylation: $\beta Zn = -0.912$; 95% CI, -1.512, -0.306; $p = 0.003$
(Issah, Arko-Mensah, Rozek, Rentschler, et al., 2022)	Cross sectional: exposed v.s reference group, Ghana	100 e-waste workers vs 51 unexposed people	$PM_{2.5}$ and PM_{10}	PM 2.5 and PM 10 concentrations: 77.32 vs 34.88, $p < 0.001$ and 210.21 vs 121.92, $p < 0.001$ Correlation between PM 2.5 and LINE-1 CpG2 ($\beta = 0.003$; 95% CI; 0.001, 0.006; $p = 0.022$); no significant difference between PM 2.5/PM 10 and other LINE-1 sites
(Li, Guo, et al., 2020)	Cross sectional: e-waste residents (RE) vs former workers (FE) vs reference residents (RF), China	23 RE vs 23 FE vs 45 RF	25 heavy metals (As, Ni, Ag, La, Ce, Cr, Mn, Ge, Co, Cd, Sn, Cu, Zn, Rb, Hg, Pb, Pr, Nd, Sm, Gd, Tb, Dy, Ho, Er, Y)	Blood total metals level: 8690.16 ng/mL vs 9383.08 ng/mL vs 8221.85 ng/mL (RE vs FE, p=0.2; RF vs RE, p=0.3; RF vs FE, p=0.04) Significant negative association observed between Ce level and 5-mc in FE (β=-0.438, p=0.046); Significant negative association observed between As level and 5-mc in RE (β=-0.245, p=0.032). No significant association between other metals and 5-mc levels.
(Li, Liu, et al., 2020)	Cross sectional: e-waste residents (RE) vs formal workers (OE) vs reference residents (RF), China	41 RE vs 36 OE vs 73 RF	17 heavy metals (Ag, As, Cd, Ce, Cr, Cu, Ge, Hg, La, Mn, Mo, Ni, Pb, Rb, Sn, Ti, Zn)	Significant positive association between Ni and MCN in RE (r=0.436, p=0.004); Significant positive association between Ni and MCN (r=0.415, p=0.012) and length of telomere (LOT) in OE (r=0.409, p=0.013)
(Z. Zeng, Xu, Wang, et al., 2022)	Cross sectional: exposed vs reference group, China	Pregnant women: 101 exposed vs 103 unexposed	$PM_{2.5}$	PM 2.5 exposure: 0.78 mg/kg·day vs. 0.52 mg/kg·day ($P < 0.001$) Association between e-waste exposure and DNA methylation at 4 CpG sites in BAI1 (cg25614253: 8.00% vs. 7.00%, P = 0.023; position +13: 83.00% vs. 76.00%, $P < 0.001$; position +32: 70.00% vs.49.00%, $P < 0.001$; position -12: 77.00% vs. 76.00%, P = 0.061)

(Berame et al., 2020)	Cross sectional: exposed vs unexposed, the Philippines	E-waste workers (n=40) vs control (n=52)	Not assessed	Higher number of micronuclei in the buccal epithelium of exposed group: 2706 out of 42336 vs 630 out of 51720, p=0.00; higher rate of binucleated (0.4% vs 0.2%) and karyolysis (2% vs 0.7%)
(Xu et al., 2020)	Cross sectional: exposed vs reference group, China	116 Pre-school children (age 3-7; 68 exposed vs 48 unexposed)	Pb and Cd	Blood Pb level=5.29ug/dL vs 3.63 ug/dL (p<0.001); Urinary Cd=1.52 ug/g cre vs 1.21 ug/g cre (p=0.323); DNA methylation difference: cg 02978827 (0.57 vs. 0.00, p < 0.05), position +14 (2.55 vs. 3.52 , p < 0.001), position +4 (2.59 vs. 3.13, p < 0.05); Negative association between MeCP2 methylation level with Pb (β = - 1.236; −2.397, −0.075). No significant associations between Rb1 and CASP8 methylation with Pb and Cd exposures.
Oxidative Stress				
(Tahir et al., 2021)	Cross sectional: exposed workers v.s reference group, Pakistan	90 e-waste workers (Repairers (n = 22) vs dismantlers (n=52) vs recovery workers (n = 16)) vs controls (n=30)	Pb, Cd, Cr, Cu, Ni, Zn and Fe	Urine metals (µg/g creatinine): Cu (63.94 vs 13.67); Zn (734.95 vs 145.00); Pb (13.19 vs 4.67); Ni (22.94 vs 4.13); Fe (153.42 vs 161.20); Cd (2.78 vs 0.81); As (23.44 vs 2.43); Cr (26.34 vs 6.40), all p<0.05 Higher MDA: smelting workers (3.22 ± 0.39 nM/mL) vs dismantlers (2.59 ± 0.62 nm/mL) vs repairers (2.12 ± 0.67 nM/mL) vs controls (1.20 ± 0.28 nM/mL) Lower SOD activity: smelting workers (162 (105–525) nM/min/mL) vs dismantlers (286 (111–707) nM/min/mL) vs repairers (429 (135–821) nM/min/mL) vs controls (503 (355–1086) mM/min/mL) Lower CAT: smelters (73.60 (61.91–93.16) µM/mL) vs dismantlers (83.26 (14.87–96.57) µM/mL) vs repairers (91.40 (67.66–113.2) µM/mL) vs controls

				(110.23 (83.29–125) µM/mL) Higher GR activity: smelting workers (0.23 (0.19–0.27) nM/mL) vs repairers (0.22 (0.17–0.28) nM/mL) vs dismantlers (0.21 (0.11–0.28) nM/mL) vs controls (0.22 (0.17–0.28) nM/mL) Exposed group had more oxidative stress-related symptoms (blurry vision, fatigue and wrinkles and grey hair) and higher blood pressure than unexposed group ($p<0.05$)
(Kuang et al., 2022)	longitudinal population study: Four years of sampling in an e-waste site, China	Population (n=760)	PAHs, VOCs, Heavy metals: Cr, Mn, Co, Ni, Cu, Mo, Cd, Sn, Ba, and Pb	Children v.s adults (ug/g cre): Urinary MDA=314 vs 202; 8-OHdG=8.45 vs 5.06 ; MU=61.6 vs 37.9; 1,2-DB=7.39 vs 5.36; PMA=0.124 vs 0.156; BMA=5.35 vs 3.89; 2-OHN=3.77 vs 4.91; 1-OHN=2.89 vs 3.87; 2-&3-OHF=0.456 vs 0.901; 2-OHPhe=0.0435 vs 0.0752; 3-OHPhe=0.118 vs 0.121; 1-&9-OHPhe=0.203 vs 0.246; 4-OHPhe=0.0811 vs 0.0672; 1-OHP=0.195 vs 0.193; Cr=3.57 vs 3.69; Mn=3.01 vs 2.15; Co=0.598 vs 0.332; Ni=6.34 vs 4.21; Cu=17.4 vs 11.8; Mo=131 vs 54.5; Cd=0.348 vs 0.828; Sn=3.5 vs 2.2; Ba=5.83 vs 4.09; Pb=5.23 vs 3.56 Positive associations observed between MDA and heavy metals (exclude Ba, Pb, Mn and Sn), all 4 VOC metabolites and PAH metabolites (exclude 2-&3-OHF, 1-OHN, 4-OHPhe and 2-OHPhe) Positive association observed between 8-OHdG and heavy metals (exclude Ni, Mn, Co and Cr), all PAHs metabolites and VOC metabolites excluding PMA. Comparison after e-waste control during 2016 to 2019: Significant reductions in urinary PAH metabolites and VOC metabolites (2-&3-OHF, 2-OHPhe,

				3-OHPhe, 1-&9-OHPhe, 4-OHPhe, 1-OHP, MU, and PMA) levels observed. No significant reductions observed in heavy metals level (exclude Sn). Urinary 8-OHdG level decreased from 9.45ug/g cre to 7.79 ug/g cre ($p<0.01$) while no significant difference in MDA levels.
(Neitzel et al., 2020)	Cross sectional: e-waste informal recycling workers in Thailand	120 workers	Cd, Pb, Mn	Urinary metal levels in men and women (ug/g cr): Cd=0.65 vs 0.7; Pb=6.58 vs 8.41; Mn=7.07 vs 23.24; Blood metal levels: Cd=0.99 vs 0.68 ug/L; Pb=4.02 vs 2.79 ug/dL; Mn=15.38 vs 16.29 ug/L No association observed between heavy metals and 8-OHdG.
(Z. Wang, Xue, et al., 2022)	Cross sectional: exposed vs unexposed, China	113 residents: exposed (n=62) vs unexposed (n=51)	Cu, Pb, Zn, Ni, Co, Sn, Cd	Significant higher levels of 4 out of 7 tested metals: Co(0.4 ng/ml vs 0.32ng/ml), Ni(4.79ng/ml vs 2.1ng/ml), Sn (0.32ng/ml vs 0.23ng/ml), Pb (37.93ng/ml vs 32.85ng/ml). Significant lower level of Zn (4831.19ng/ml vs 5312.01ng/ml) in the exposed group. No difference in Cd and Cu levels. Higher level of OS markers: MDA (6.43 pg/mL vs 5.24 pg/mL) and 8-I (1210.94 pg/mL vs 1021.72 pg/mL), all $p<0.05$ Significant positive association between Ni with MDA, and between Co with Tn
(Xue et al., 2021)	Cross sectional: exposed vs reference group, China	109 residents: exposed (n=62) vs unexposed (n=47)	Cu, Pb, Zn, Ni, Co, Sn, Hg, Cd	4 out of 8 tested metals were significantly higher in the exposed group: Pb (39.88ng/ml vs 33.49ng/ml), Ni(4.69 ng/ml vs 2.11ng/ml), Co (0.42 ng/mlvs 0.33ng/ml), Hg (3.77ng/ml vs 2.00ng/ml). No significant difference in Cu, Zn, Sn and Cd. Elevated levels of 8-I (1309.19pg/ml vs 1175.00pg/ml) and MDA (6.53 pg/ml vs 5.79pg/ml) in the exposed group.
(Li et al.,	Cross sectional:	E-waste site	Co, Ni, Hg, Sn,	Exposed group showed significantly

2021)	exposed vs unexposed, China	residents (n=69) vs reference residents (n=51)	Cd, Cu, Pb and Zn	higher Co, Ni, Hg, and Sn in blood; no significant difference in Cd, Cu, Pb and Zn. Blood-brain barrier permeability and oxidative stress biomarkers except 5-HT were higher in exposed group Positive correlation between blood Co level and biomarkers of blood-brain barrier dysfunction
5-mc - 5-Methylcytosine; BAI1 - Brain-specific angiogenesis inhibitor 1; LINE -1 - Long interspersed nucleotide elements-1; MCN - mitochondrial DNA copy number; Cre - Creatinine; PAH - Polycyclic aromatic hydrocarbon; OH-PAHs - monohydroxy-PAHs; MDA - Malondialdehyde; SOD - serum superoxide dismutase; CAT - Catalase; GR - Glutathione reductase; 8-OHdG - 8-Hydroxy-2'-deoxyguanosine; OS - oxidative stress; TGF-β - Transforming growth factor beta; α-SMA - Alpha-Smooth Muscle Actin; 8-I - 8-isoprostane; PMA - s-phenylmercapturic acid; Sn - urinary tin; MU - trans-muconic acid				
Table 3: E-waste Exposure and Genotoxicity and Oxidative Stress				

Respiratory, cardiovascular and hematological changes:

There were three studies identified about e-waste related respiratory impacts, all of them found significant reduction in lung function or elevated levels of fibrosis biomarkers among exposed groups. Amoabeng Nti et al. found higher PM exposure from e-waste burning was significantly associated with lower PEF and FEF values; for e-waste workers who had asthma history, e-waste burning was also associated with reduced PEF and FEV, which are indicators of lung function. Wachinou et al. also found significantly much higher rates of respiratory symptoms, chest tightness, breathlessness, and lung function disorders in e-waste workers than unexposed groups; and e-waste recycling work was also associated with reduced FEV and FVC. Moreover, higher blood Co level was also found to be associated with elevated levels of fibrosis biomarkers including α-SMA and TGF-β among e-waste sites residents in China (Xue et al., 2021).

Five studies about cardiovascular impacts were identified for this review, all of which reported some levels of negative impacts on cardiovascular function related to e-waste exposure. One study in Ghana measured PM levels in four different seasons and their relationship with heart function. The study found significantly higher exposure of PM and lower heart rate variability among e-waste workers in all seasons except in Harmattan season, in which the PM levels were the highest throughout the whole year. They also found a negative association between $PM_{2.5}$ and MeanNN interval, and a negative but small association between $PM_{10–2.5}$ and LF/HF, but not with other heart variability indexes (Amoabeng Nti et al., 2021). Moreover, Chen et al., found significant elevated levels of Pb among exposed preschoolers in China and associated impaired heart function including smaller left ventricle (LV) and impaired systolic LV function. In terms of blood pressure, one study in Indian e-waste workers found higher levels of Pb were associated with higher diastolic blood pressure, but not with systolic blood pressure or pulse rate. However, elevated PAH exposure associated with decreased systolic blood pressure and pulse pressure were found among preschool children at a Chinese e-waste site. This study also found associations between decreased antioxidative enzymes including SOD and GPx with decreased systolic blood pressure. Moreover, one study also found significantly higher levels of Ni exposure among e-waste site residents, which were associated with higher MDA and two indicators for coronary heart disease, troponin (Tn) and myeloperoxidase (MPO) (Z. Wang, Xue, et al., 2022).

Three studies about hematological effects were identified, two of them did not find significant changes in hematological effects related to e-waste exposure (Upadhyay et al., 2021) (Zhou et al., 2020). Only one Chinese study found significantly lower levels of hemoglobin levels and higher anemia prevalence in high blood Pb children that were associated with e-waste exposure (H. Wang et al., 2021).

	Study design	**Exposed population**	**Major Toxicants**	**Health Impacts**
Respiratory:				
(Amoabeng Nti et al., 2020)	longitudinal cohort study: e-waste workers vs control group, Ghana	142 e-waste workers vs 65 control	$PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10}	PM level in dry season (94.26 µg/m3 vs. 68.23 µg/m3; p = 0.009), rainy season (48.88 µg/m3 vs. 34.74 µg/m3; p = 0.009) and harmattan season (54.30 µg/m3 vs. 31.59 µg/m3; p = 0.960) Negative associations between PM exposure and lung function: PEF (β = −3.133; 95% CI: −0.243 to −0.022), FEF (β = −0.266; 95% CI: −0.437 to 0.094) E-waste burning and asthma history were significantly associated with decreased PEF (β = −0.142; 95% CI: −0.278, −0.008) and FEV1 (β = −0.358; 95% CI: −0.590, 0.125)
(Wachinou et al., 2022)	Cross sectional study: e-waste workers vs unexposed populations, Benin	148 e-waste workers vs 148 control	Not assessed	Respiratory symptoms: 33.1% vs. 21.6% (p=0.027); Chest tightness: 11.8% vs. 2.1% (p=0.003); Breathlessness: 6.8% vs. 1.4% (p=0.018); all lung function disorder: 25.0% vs. 14.9% (p=0.029); E-waste work is significantly associated with decrease of FEV1 by 0.42 L (95% CI: 0.29 L-0.55 L) and of FVC by 0.75 L (95% CI: 0.59 L-0.91 L)
(Xue et al., 2021)	Cross sectional: exposed vs reference group, China	109 residents: exposed (n=62) vs unexposed (n=47)	Cu, Pb, Zn, Ni, Co, Sn, Hg, Cd	Elevated levels of TGF-β (6580.36pg/ml vs 5713.32 pg/ml) and α-SMA (634.76 pg/ml vs 597.10 pg/ml)in the exposed group. Positive association between Co with α-SMA (β = 323.18, p = 0.03) and TGF-β (β = 4814.69, p < 0.01) in the exposed

				group. No significant association found between other metals and any fibrosis biomarkers.
Cardiovascular:				
(Amoabeng Nti et al., 2021)	Longitudinal: e-waste workers vs reference group, Ghana	142 e-waste workers vs 65 control	Particulate matters ($PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10})	E-waste workers showed significantly lower heart rate variability than unexposed groups in all seasons except mean NN in Harmattan season. Negative association between $PM_{2.5}$ and MeanNN interval (β=− 0.76 95% CI: − 1.48, − 0.04); negative but small association between $PM_{10–2.5}$ and LF/HF (β=− 0.004 95% CI: − 0.402, − 0.032) ; no significant associations observed between other HRV index and PM
(Z. Chen et al., 2021)	Cross sectional: exposed children vs reference children, China	Pre-school children (age 3-7) 319 exposed vs 176 unexposed	Pb	Blood Pb level: 4.51 ug/dL vs 3.98 ug/dL ($p<0.001$) Lower echocardiographic LV patterns including smaller LV and impaired systolic LV function in both male and female
(Upadhyay et al., 2021)	Cross sectional: e-waste informal recycling at 2 recycling sites, India	E-waste workers: 32 from site 1 vs 32 from site 2	Pb	Blood lead levels: 5.68 ug/dL vs 2.41ug/dL, $p<0.0001$; Diastolic BP: 78.15 mmHg vs 71.48mmHg, $p=0.02$; no significant difference in systolic BP or Pulse rate;
(Q. Wang, Xu, Zeng, Zheng, et al., 2020)	Cross sectional: exposed children vs reference children, China	403 pre-school children (age 2-7) 203 exposed vs 200 unexposed	PAHs	Urine ∑8OH-PAHs level: 6.438 ug/L vs 5.709 ug/L Negative association between PAH exposure with systolic pressure (β = −0.091), pulse pressure (β =−0.104), SOD (β =−0.154), GPx (adjusted β = −0.332, only in unexposed children) and plasma vitamin E (adjusted OR = 0.838, 95% CI: 0.706, 0.995, only in exposed children). Positive association between blood

				pressure with serum SOD (β for diastolic pressure = 0.215, β for systolic pressure = 0.193, β for pulse pressure = 0.281) and GPx (β for GPx-T2 = 0.283 and β for GPx-T3 = 0.289 for diastolic pressure in unexposed children, all $P < 0.05$)
(Z. Wang, Xue, et al., 2022)	Cross sectional: exposed vs unexposed, China	113 residents: exposed (n=62) vs unexposed (n=51)	Cu, Pb, Zn, Ni, Co, Sn, Cd	Higher level of CHD biomarkers: Tn (576.11 ng/mL vs 523.18 ng/mL) and MPO (183.38 ng/mL vs 163.13 ng/mL); Significant positive association between Ni with Tn and MPO
Hematological:				
(H. Wang et al., 2021)	Cross sectional: exposed vs unexposed, China	428 children (aged 3-6 years): exposed (n=224) vs unexposed (n204)	Pb	Blood lead level: 8.5 vs 6.0 ug/dL, p=0.00 Lower Hb values in high blood lead (>5ug/dL) groups: blood Pb level 5.0–9.9 µg/dL group: 122.6 g/L vs 125.8 g/L ; Blood Pb ≥ 10.0 µg/dL: 120.3 g/L vs 123.6g/L. No significant difference in low blood lead groups (<5ug/dL) Prevalence of anemia: 4.0% vs 0.5% in ≥ 10.0 µg/dL group; 5.4% vs 1.5% in BLL 5.0–9.9 µg/dL group (both p=0.03). No significant difference in low blood Pb group (<5ug/dL); no significant association between blood Pb level and iron deficiency.
(Zhou et al., 2020)	Cross sectional: exposed vs unexposed, China	112 residents: exposed (n=54) vs unexposed (n=58)	PBDEs	PBDEs : 240.00 ng/g vs 93.00 ng/g, p<0.05. No significant difference in most hematological indexes except mean platelet volume, plateletcrit, basophils percentage, absolute value of basophils, and mean corpuscular hemoglobin concentration which were higher in the exposed group.
(Upadhyay et al., 2021)	Cross sectional: e-waste informal recycling at 2	E-waste workers: 32 from site 1 vs 32 from	Pb	Significant difference in Pb exposure (see above) No significant difference in hematological

	recycling sites, India	site 2		parameters among two groups.
PM - particulate matter; PEF - Peak Expiratory Flow; FEF - forced mid-expiratory flow; FEV - Forced expiratory volume; FVC - Forced vital capacity; Tn - troponin; MPO - Myeloperoxidase; HRV - heart rate variability; BP - blood pressure; SOD - serum superoxide dismutase; PAHs - Polycyclic aromatic hydrocarbons; GPx - serum glutathione peroxidase; LF - low-frequency power; HF - high-frequency power; LV - left ventricle; Hb - hemoglobin; PBDEs - Polybrominated Diphenyl Ethers				
Table 4: E-waste Exposure and Respiratory, Cardiovascular and Hematological Changes				

Auditory, reproductive, renal, oral, metabolic and gut impacts:

Two studies investigated the association between hearing loss and e-waste. Carlson et al., measured the noise level at an e-waste recycling site in Ghana and found the daily average noise exceeded WHO safe level. They also found a high prevalence of hearing loss among workers associated with noise exposure, but not with heavy metal levels (Carlson et al., 2021). Moreover, another study found elevated blood Pb levels due to e-waste exposure among preschool children was associated with higher risks of hearing loss in left ears (Xu et al., 2020).

Two studies about the renal impacts associated with e-waste exposure were identified. Guo et al., found significantly higher levels of PCBs, PBDEs, NFRs among exposed students, but no difference in Pb, Cd or Ni. They also found elevated levels of PCBs, PBDEs and NFRs exposures were positively associated with levels of two renal function indexes (β2-MG ,UA), but negatively associated with other two indexes (BUN, SCr), and not associated with NAG (L. C. Guo et al., 2023). (Neitzel et al., 2020) also found higher levels of metals exposure and higher glomerular filtration rate associated with the elevated Pb levels among e-waste workers in Thailand (Neitzel et al., 2020).

Three studies, all conducted at Ghana, investigated the musculoskeletal discomfort and physical Injuries rate in e-waste workers. Two of them found significantly higher prevalence of pain and injuries associated with e-waste work among e-waste workers (Acquah et al., 2021) (Fischer et al., 2020). The other one study found more than 90% of e-waste workers reported cuts and scars due to their work; the prevalence of abrasions and burns were also high among e-waste workers (Adusei et al., 2020).

Three papers studied the metabolic impacts associated with e-waste work. Two studies found significantly higher urinary levels of PAHs among children who live near to e-waste recycling sites. Dai et al found lower levels of cytochrome P450 enzymes were associated with higher levels of urinary PAHs metabolites (Dai et al., 2022). Moreover, Wang et al also studied the PAHs levels among preschool children, found children who have higher PAHs levels and lower SOD levels were more likely to have higher dyslipidemia risk (Q. Wang, Xu, Zeng, Hylkema, et al., 2020). In a Ghana study, high levels of Pb but not Cd were found among exposed children; however, no significant associations between blood Pb and glucose levels were found among these children (Dawud et al., 2022).

Other articles also studied the oral, reproductive, gut, neuro-degenerative and mental health impacts related to e-waste exposure. Zhang et al., found elevated blood Pb levels were associated with weaker oral antimicrobial activities such as lower salivary agglutinin concentrations and higher monocyte percentage among e-waste exposed children. Negative associations were also found between PCBs exposure and reproductive health among male residents in e-waste sites: higher PCBs levels were associated with reduced semen volume, sperm concentration and higher sperm abnormality rate. In addition, elevated Pb levels due to e-waste exposure were also associated with reduced gut microbiome diversity and among children. One article studied the neuro-degenerative impacts of e-waste exposure, and found higher levels of three indicators of cognitive impairment (EHMT1, BAZ2B and MDA) but lower levels of two indicators (Aβ42 and BNDF) among the exposed group. They also didn't find significant association between metals exposure and in Aβ40 or Aβ42/Aβ40. One study surveyed e-waste workers in five western African countries and found a significantly higher prevalence of work-related stress, insufficient income, violence at work, poor work-life balance and overwork among e-waste workers.

Auditory:				
(Carlson et al., 2021)	Descriptive: informal recycling in Ghana	58 e-waste workers	Noise and metals: As, Cd, Pb, Mn, Hg, Cu, Fe, Sn, Zn	Daily average noise: 74.4–90.0 dBA Blood metal mean level ug/L: As (4.63), Cd (2.97), Pb (97.2), Mn (12.6), Hg (1.8), Cu (1061), Fe (440161), Se (163.6), Zn (5539) 25.9% reported having trouble with hearing. 67% reported ear ringings. 76% bothered by occupational noise. No significant association between Pb, Hg , Cd, Zn and hearing loss. Positive association between Se and hearing at 6 kHz.
(Xu et al., 2020)	Cross sectional: exposed vs reference group, China	116 Pre-school children (age 3-7; 68 exposed vs 48 unexposed)	Pb and Cd	See above for exposure levels Blood Pb level is associated with hearing loss in the left (OR=1.46, 95% CI: 1.12 to 1.91) and both ears (OR=1.40, 95% CI 1.06 to 1.84)
Renal:				
(L. C. Guo et al.,	Cross sectional: exposed vs	114 Sixth-grade	PCBs, PBDEs, NFRs, Pb, Cd,	ΣPCB, ΣPBDE, and ΣNFR levels were significantly higher in exposed groups (

2023)	unexposed, China	students: exposed (n=57) vs unexposed (n=57) 112 adults: exposed (n=54), unexposed (n=58)	Ni	both adolescents and adults). No significant difference in Pb, Cd and Ni levels between different groups. PCBs, PBDEs and NFRs: Positive association in two renal function indexes (β2-MG ,UA), negative association in other two indexes (BUN, SCr), no significant association with NAG. Negative association between UA level with ΣPBDE and Cd interaction. Positive association between β2-MG levels with ΣPBDE and Cd interaction
(Neitzel et al., 2020)	Cross sectional: e-waste informal recycling workers in Thailand	120 workers	Cd, Pb, Mn	Urinary metal levels see above; Significant positive association between glomerular filtration rate and urinary Pb levels (β=1.01, p=0.001).
Oral:				
(S. Zhang et al., 2020)	Cross sectional: exposed vs reference group, China	116 Pre-school children (age 3-7; 101 exposed vs 106 unexposed)	Pb	Blood Pb level: 4.89 ug/dL vs 3.47 ug/dL ($P<0.001$) Negative association between blood Pb level with saliva SAG concentration: B (95% CI) = − 1.813 (− 3.490, − 0.136), $P < 0.05$; positive association between Pb and peripheral monocyte percentage by mediating saliva SAG concentration: B (95% CI) = 0.081 (0.016, 0.201), $P < 0.05$.
Musculoskeletal discomfort and physical Injuries				
(Acquah et al., 2021)	Cross sectional: exposed group v.s reference group, Ghana	Informal workers (n=176) v.s unexposed group (n=41)	Not assessed	Collectors have higher average pain scores (83.7 ± 10.6) than dismantlers (45.5 ± 7.6), burners (34.0 ± 9.1), and the unexposed group (26.4 ± 5.9).
(Fischer et al., 2020)	Cross sectional: exposed group v.s reference group, Ghana	Informal workers (n=84) v.s bystanders	Not assessed	Red itchy eyes: 67.9% v.s 51.6%; back pain 91.6% v.s 79.6% ; work-related injuries 75.0% v.s 42.6%.

		(n=94)		
(Adusei et al., 2020)	Descriptive:Informal recycling in Ghana	112 workers	Not assessed	Prevalence of cut: 96.2%; abrasion: 16.3%; scars: 93.6%; burns: 23.1%
Reproductive:				
(Lin et al., 2021)	Cross sectional: e-waste recycling area, China.	76 male residents living in e-waste recycling area	PCBs	Negative associations between semen volume and levels of CB153 ($\beta = -0.258$, 95% CI: –0.521 to 0.005, $p = 0.054$) or ΣDioxin-like PCBs ($\beta = 0.348$, 95% CI: 0.086–0.611, $p = 0.010$) Negative association between CB105 and 66 levels and sperm concentration. Positive association between two sperm abnormal morphology indexes (TZI and SDI, with CB44 and 180 semen levels. No significant association between PCB congeners levels in semen and reproductive hormones
Gut:				
(X. Zeng, Zeng, Wang, et al., 2022)	Cross sectional: exposed vs unexposed, China	70 children (aged 3-7 years): exposed (n=34), unexposed (n=36)	Pb	Pb blood level: 5.81ug/dL (5.41, 6.56) vs 1.98ug/dL (1.64, 2.26), ($p < 0.001$); Pb urinary level: 0.36 ug/L (0.20, 0.81) vs 0.14 ug/L (0.09, 0.21), ($p < 0.001$). Gut microbiome diversity was lower in exposed group Positive association between blood lead level and Goods coverage ($r = 0.448$, $P < 0.001$). Negative association between blood lead level with Chao ($r = -0.378$, $P < 0.001$), Observed species ($r = -0.265$, $P < 0.001$), Phylogenetic diversity ($r = -0.368$, $P < 0.001$), Shannon ($r = -0.126$, $P > 0.05$) and Simpson ($r = -0.013$, $P > 0.05$)
Neuro-degenerative:				
(Zhu et al., 2021)	Cross sectional: exposed residents vs unexposed,	99 exposed residents vs 96 unexposed	26 metals: Cr, Mn, B, Ti, Ge, As, Co, Ni, Mo, Ag, Cd,	All metals except Ge, Cd, Cu, Zn, Na were significantly different between two groups.

	China	residents	Sb, Ba, Pt, Cs, Cu, Zn, Rb, Hg,Pb, La, Ce, Ca, Fe, K and Na	Higher EHMT1 (437.62 vs 374.19, p=0.001), higher BAZ2B (979.37 vs 892.68, p=0.008), lower Aβ42 (1012.15 vs 1412.72, p=0.036), lower BDNF (3263.23 vs 12900.90. p<0.001) and higher MDA (6.43 vs 5.43, p=0.001). No significant association in Aβ40 or Aβ42/Aβ40. Positive association between Ag and MDA (β=0.307 95%CI 0.12 to 0.504) and EHMT1 (β=0.375, 95%CI 0.213 to 0.537)
Mental:				
(Kêdoté et al., 2022)	E-waste workers in 5 West African countries	740 e-waste workers	Not assessed	Work related stress is associated with insufficient income (OR: 1.46; CI95: [1.03–2.08]; p = 0.036), violence at work (OR: 3.07; CI95: [1.21–10.40]; p = 0.036), work interference with family/leisure responsibilities (OR: 2.41; CI95: [1.42–4.31]; p = 0.002), working seven days a week (OR: 1.67; CI95: [1.12–2.52]; p = 0.014)
Metabolic:				
(Dai et al., 2022)	Cross sectional: exposed group v.s reference group, China	100 children (aged 3-6 years): exposed (n=50), unexposed (n=50)	PAHs	All urinary OH-PAHs were significantly higher in exposed group than in control group ΣOH-PAHs in the 2nd and 3rd quartiles was associated with lower CYP-derived 5,6-EET [2nd quartile: B 95%CI =-0.189 (− 0.314, − 0.064); 3rd quartile: B= − 0.229 (− 0.357, − 0.100)], lower 11,12-EET [2nd quartile: B=− 0.126 (− 0.246, − 0.007); 3rd quartile: B= − 0.136 (− 0.258, − 0.014)], and lower 14,15-EET [2nd quartile:B= − 0.166 (− 0.311, − 0.022); 3rd quartile: B=− 0.178 (− 0.326, − 0.030)] than in the 1st quartile. ΣOH-PAHs in the 3rd quartile was associated with lower CYP-derived 16(17)-epoxydocosapentaenoic acid (EpDPE) [B 95%CI= − 0.186

				(− 0.330, − 0.043)], but higher CYP-derived 9,10-DiHOME [B 95%CI =0.066 (0.013, 0.129)]
(Dawud et al., 2022)	Cross sectional: exposed residents vs unexposed, Ghana	151 participants: e-waste workers (n=100) vs control group (n=51)	Pb and Cd	Blood Pb: 92.35 ug/dL vs 40.67 ug/dL; Blood Cd: 0.73 ug/dL vs 0.93 ug/dL Diabetes prevalence: 31% vs 41%; No significant association between Pb or Cd exposure and blood glucose levels
(Q. Wang, Xu, Zeng, Hylkema, et al., 2020)	Cross sectional: exposed residents vs unexposed, China	403 pre-school children (age 2-7) 203 exposed vs 200 unexposed	PAHs	Urine ∑8OH-PAHs level: 6.438 ug/L vs 5.709 ug/L Children with higher ∑3OH-Phes and lower SOD had higher dyslipidemia risk than children without either risk: β=5.594(95% CI: 1.119, 27.958)
CYP - cytochrome P450; β2-MG - β2-microglobulin; BUN - blood urea nitrogen; SCr - serum creatinine; NAG - N-acetyl-β-d-glucosidase; UA - uric acid; SAG - salivary agglutinin; BDNF - Brain-derived neurotrophic factor; Aβ42 - β-amyloid protein 42; EHMT1 - Euchromatic Histone lysine Methyltransferase 1; BAZ2B - Bromodomain Adjacent to Zinc finger domain 2B; MDA - Malondialdehyde				
Table 5: E-waste Exposure and Auditory, Reproductive, Renal, Oral, Metabolic and Gut impacts				

Discussion:

This literature review provides an update on the population-based evidence concerning e-waste informal recycling and human health. Consistent with the previous two literature reviews by Grant et al and Parvez et al, the current review also found significant evidence of higher toxic chemicals exposure from e-waste informal recycling and associated adverse health effects in recyclers and nearby residents. Exposure to heavy metals, air pollutants and POPs such as PAHs, PBDEs, dioxins, especially during critical developmental windows such as pregnancy and early childhood, was found to have negative impacts on growth, neurological development, immunological and hormonal functions, epigenetic changes, inflammation and organ functions. Nevertheless, due to the diverse outcomes and broad exposure variables, it is difficult to draw quantified conclusions about specific associations, such as dose-response relationships, based on the current evidence. In addition to the previous reviews, more current literature focused on the health impacts by emerging contaminants such as rare metals and NFRs, rather than traditional toxic chemicals such as Pb and PCBs, indicating a tendency of changing manufacturing processes and phasing out old toxicants while incorporating new toxicants at the same time (e.g., using NFRs as an alternative of PCBs; lead free solder that is alloyed with potential toxic rare earth elements) (EPA, 2015) (C. M. L. Wu et al., 2004). Furthermore, more literature measured the social-economic health determinants related to e-waste recycling work, pointing out that health impacts from e-waste recycling were not only associated with chemical pollution but were also associated with the social environment that e-waste workers and their families were experiencing.

Some potential mechanisms have been proposed to explain the negative effects associated with e-waste exposure, although the exact mechanisms were not fully understood. A large body of current evidence focuses on the effect on endocrine systems. Metals can potentially alter immune functions by inducing excess oxidative stress and inflammation. Studies have found that elevated metal levels were associated with increased proinflammatory cytokines, decreased anti-inflammatory cytokines, and excess oxidative stress biomarkers such as MDA in both immune cells and endocrine cells, which can lead to reduced immune responses and abnormal hormone expressions (Y. Zhang et al., 2020) (C. Guo et al., 2021) (C. Guo et al., 2020) (Li, Li, et al., 2020).

Moreover, some heavy metals such as Cd, Hg, Pb, As, Mn and Zn are endocrine disruptors themselves. Studies have found that those metals may interfere with hormone levels through binding with hormone receptors, inhibit or stimulate transcription or expression activities, and increase oxidative stress (Iavicoli et al., 2009). For POPs such as PAHs, PBDE, PCBs, dioxins, etc., they were also found to act as endocrine-disrupting chemicals which disturb the normal hormone secretion, enzyme activities and have antagonistic action on hormone receptors (Shi et al., 2020) (Lin et al., 2021) (Gravel et al., 2020). Furthermore, evidence found the alterations of immune responses and hormone levels due to e-waste exposure can impact renal, reproductive, and metabolic functions (L. C. Guo et al., 2023) (Lin et al., 2021) (Q. Wang, Xu, Zeng, Hylkema, et al., 2020).

Many studies also investigated the DNA damage and epigenetic effects by e-waste exposure. Studies have found that heavy metals can alter the LINE-1 CpG2 DNA methylation through increasing oxidative stress level and decreasing the activities of several DNA methyltransferases that regulate the DNA methylation process (Issah et al., 2021) (Issah, Arko-Mensah, Rozek, Zarins, et al., 2022) (Issah, Arko-Mensah, Rozek, Rentschler, et al., 2022) (Li, Guo, et al., 2020). Evidence also suggests that metals can damage mitochondrial DNA, which is associated with higher cancer risks (Li, Liu, et al., 2020). Moreover, the alterations of DNA methylation due to e-waste exposure were found to be associated with increased cell apoptosis, hormonal dysfunction and smaller head circumferences of newborns (Xu et al., 2020) (Z. Zeng, Xu, Wang, et al., 2022).

Finally, studies also pointed out some social behavioral factors that may exacerbate the negative health effects from chemical exposure. Several studies have pointed out that e-waste workers and their families were more likely to have less education, less household income, low health literacy, and were more likely to work in unpleasant environments, experiencing discrimination and mental stress. The prevalence of insufficient dietary macronutrient and micronutrient intake among e-waste workers can pose additional risk of toxicant exposure and adverse health outcomes (Dawud et al., 2022) (Goyer, 1995). E-waste workers also experienced significantly higher levels of psychological stress due to low salaries, long working hours, and violence from work (Kêdoté et al., 2022). In Africa, e-waste workers are often not protected by occupational safety standards, which results in frequent cuts, burns, muscular discomfort, and exposure to unsafe levels of noises (Acquah et al., 2021) (Fischer et al., 2020) (Adusei et al., 2020) (Carlson et al., 2021). Studies have also shown that the percentages of smoking or exposure to secondhand smoke is higher among the exposed groups than reference groups, which adds an additional risk of adverse health effects (Xu et al., 2020) (Wachinou et al., 2022) (Berame et al., 2020). Moreover, children who washed their hands less frequently or had hand-to-mouth behaviors or chewing pencils habits were more likely to have higher levels of toxicants in their bodies (Xu et al., 2020).

Among the studies included in this review, one strength is that many of them adjusted for common confounders such as education, income, smoking history, hand-washing habits, which can reduce potential bias. This is in contrast to previous reviews conducted in 2013 and 2021, where none of the studies accounted for these confounders. Another strength is that many studies used biomarkers to measure chemical exposure, which is more objective than using self-reported data or questionnaires. However, using biomarkers can also lead to potential bias since they can only reflect the most recent exposure, but not long term or previous exposure that occurred many years ago. In addition, biomarkers levels may be influenced by chemical exposures from daily activities other than e-waste, such as consumer products, food packages, air pollution, making it difficult to identify specific e-waste exposure.

Another strength of this current review is the diversity of the study populations. Unlike previous reviews where over 90% of studies were conducted in the two largest e-waste sites in China, one third of the most recent evidence in this review comes from Africa and Southeast Asia. However, this may also indicate that e-waste informal recycling has become prevalent worldwide. One possible reason why the majority of studies in previous reviews came from China is because China used to be the largest e-waste receiver in the world, receiving 70% of global e-waste (UNEP, 2009). As China has tightened e-waste importation ban more strictly, e-waste importation amount was estimated to be negligible in 2023 (X. Zeng, Gong, et al., 2016). Since then, much e-waste from high-income countries has been transported to Africa and Southeast Asia, which partially explains why studies from these areas are becoming more prevalent in the current review.

There were also several limitations of the current review. One of the biggest limitations is that most of the studies were cross-sectional, which can't show long term relationships. Very few studies followed participants for an extended period of time, and there is a lack of studies investigating diseases that have long latency periods, such as cancer and cardiovascular diseases. For example, many studies focused on investigating birth outcomes associated with e-waste exposure, but the health outcomes later in the newborn's lifetime were not studied. Another example is that most studies that focus on birth and developmental outcomes only measured the exposure levels of participants once, failing to show the different impacts from exposures at specific critical developmental windows, such as early pregnancy and early childhood.

Nevertheless, there were still some improvements: three studies included in the current review were prospective cohort studies that followed participants for years; one study also showed decreased exposure levels and improved health outcomes several years after shutting down all informal recycling activities (Kuang et al., 2022). In contrast, in the 2013 and 2021 reviews, none of the studies were longitudinal.

Another limitation is the relatively small sample size: except for one study that recruited 740 participants, all other studies had relatively small cohorts, which were less than 500 persons. Although a small sample size may cause bias, the findings from these studies were generally consistent regarding the relationship between e-waste exposure and negative health impacts.

Finally, the prevalence of selective reporting, poor study designs, multiple publications based on the same dataset, statistically significant but subtle biomarker outcomes, among other factors, among studies can all lead to potential bias. The generally low quality of studies was probably due to the lack of infrastructure, such as epidemiological dataset, limited funding, and insufficient public health workforce in developing countries. In fact, none of these countries have a national public health database that can be used to conduct large epidemiological studies; nor did these studies receive funding or workforce from international organizations or developed countries to support long-term longitudinal studies in large populations. Therefore, there is an urgent need to invest in these countries and support their research on e-waste and long-term health effects.

E-waste informal recycling is a global environmental justice issue. Much of the e-waste recycled in developing countries were not produced there but were illegally imported from high-income countries in Europe, North America and Oceania. According to estimates from the Global E-waste Monitor 2022, only 9% of e-waste movements were within continents; 51% of e-waste movements were under control and across continents, while 38% of e-waste movements were uncontrolled and across continents (Baldé et al., 2022). The uncontrolled e-waste transboundary movement of e-waste and the prevalence of informal recycling were driven by many factors. The primary reason is the relatively cheap labor and lack of safety environmental standards for pollution control in low- and middle-income countries, making informal e-waste recycling much less expensive than formal recycling (Shittu et al., 2021). Even in countries that have strict regulations and standards such as China, illegal informal recycling was still prevalent because the formal sector was far less competitive to consumers, as the informal sector often paid them for e-waste (Yanzhu Zhang, 2018). Secondly, importing e-waste is still attractive for some developing countries because it can bring many economic benefits. In fact, the value of e-waste generated per year is worth $62.5 billion, which is more than most countries' Gross Domestic Product (World Economic Forum, 2019). Accordingly, e-waste informal recycling industries are highly profitable and have created jobs for 15–20 million people worldwide (Davey & Walsh, 2019). The importation of e-waste also provides cheap second-hand electronic devices for people who can't afford brand new devices in developing countries (Widmer et al., 2005). Thirdly, the lack of regulation or adequate law enforcement on e-waste smuggling also perpetuates the status quo (Jangre et al., 2022; Patil & Ramakrishna, 2020; Shittu et al., 2021). According to the Global E-waste Monitor, only 78 of the 193 countries have national e-waste legislation, regulation, or policy until 2019. The Basel Convention, an international treaty that controls the transboundary movement of e-waste, was signed by 187 countries but not all countries, and the U.S was one of the exceptions that didn't ratify this convention (United States Department of State, 2023). The Basel Convention also failed in making an agreement in the definition of e-waste, leaving room for the smuggling of e-waste marked as "used e-products" for reuse purpose (Forti et al., 2020). Moreover, due to the voluntary reporting mechanism, less than half of the signed countries reported their national e-waste data, making it difficult to monitor and regulate the illegal trading (Forti et al., 2020). Finally, other factors such as a lack of infrastructure to support formal recycling, a lack of awareness and environmental education in the general public, and so on, in developing countries, all lead to the improper and insufficient e-waste recycling.

According to estimates, If all e-waste is properly recycled, it can generate more than $62.5 billion value per year (World Economic Forum, 2019). In addition to policy, law and regulation, green chemistry and engineering can also provide potential solutions to prevent further pollution and create environmental and economic benefits. E-waste management includes green product design and proper recycling. Some principles in green design include using less toxic chemicals, more recyclable components rather than disposable materials, fewer overall materials, and less energy and resources during manufacturing, usage, and end of life handling while maintaining the same functions as in the traditional design (Paul T. Anastas & Julie B. Zimmerman, 2003). For example, e-products can be made by fewer components and designed to have extended use lifetime through modular, upgradable design as well as designed for disassembly; they can also be manufactured with fewer non-recyclable plastics that contain many toxic chemicals (Jaiswal et al., 2015). Green design innovations such as lead free solder, nickel and cobalt free batteries and PCB free electronics were also implemented in many countries (Jaiswal et al., 2015) (Young-hye Na, 2019) (EPA, 2015). Proper e-waste recycling refers to extract reusable substances from e-waste in controlled manner and reuse the substances in the manufacturing process while eliminating the concept of waste using the concepts and ideals of biomimicry (Misra et al., 2021). Instead of manually and thermally recycling metals which currently exist in informal recycling, proper recycling can use green chemical innovations to extract metals safely. For example, there are some biological treatments including bioleaching, biosorption, phytoremediation and bioelectrochemical systems to recover metals from e-waste (Dutta et al., 2023). Those biological methods use microbes and are more cost-effective and less hazardous than traditional pyrometallurgy and hydrometallurgy methods (Dutta et al., 2023). By incorporating the circular economy principles into e-waste management, e-waste can become an asset of resources, which reduces production cost, minimizes potential pollution, mitigates hazardous exposures, and generates jobs and profits. In order to tackle the soaring e-waste problems, international organizations and governments should encourage green products designs, using alternatives for toxic chemicals and provide financial and technical support to the proper recycling infrastructure in developing countries. One of the policy tools to encourage green innovation is the extended producer responsibility (EPR). EPR requires producers to be responsible for the environmental costs of their products, including end-of-life costs; producers can be incentivized for designing their products that minimize the environmental impacts from their product life-cycles (OECD, 2006). The legislation of EPR effectively encourages green manufacturing and recycling innovations, as well as raising public awareness in environmental protection (Cao et al., 2016) (Atasu & Subramanian, 2012).

References:

Acquah, A. A., D'Souza, C., Martin, B. J., Arko-Mensah, J., Dwomoh, D., Nti, A. A. A., Kwarteng, L., Takyi, S. A., Basu, N., Quakyi, I. A., Robins, T. G., & Fobil, J. N. (2021). Musculoskeletal Disorder Symptoms among Workers at an Informal Electronic-Waste Recycling Site in Agbogbloshie, Ghana. *Int J Environ Res Public Health*, *18*(4). https://doi.org/10.3390/ijerph18042055

Adusei, A., Arko-Mensah, J., Dzodzomenyo, M., Stephens, J., Amoabeng, A., Waldschmidt, S., Löhndorf, K., Agbeko, K., Takyi, S., Kwarteng, L., Acquah, A., Botwe, P., Tettey, P., Kaifie, A., Felten, M., Kraus, T., Küpper, T., & Fobil, J. (2020). Spatiality in Health: The Distribution of Health Conditions Associated with Electronic Waste Processing Activities at Agbogbloshie, Accra. *Ann Glob Health*, *86*(1), 31. https://doi.org/10.5334/aogh.2630

Alabi, O. A., Adeoluwa, Y. M., & Bakare, A. A. (2020). Elevated Serum Pb, Ni, Cd, and Cr Levels and DNA Damage in Exfoliated Buccal Cells of Teenage Scavengers at a Major Electronic Waste Dumpsite in Lagos, Nigeria. *Biological Trace Element Research*, *194*(1), 24–33. https://doi.org/10.1007/s12011-019-01745-z

Amoabeng Nti, A. A., Arko-Mensah, J., Botwe, P. K., Dwomoh, D., Kwarteng, L., Takyi, S. A., Acquah, A. A., Tettey, P., Basu, N., Batterman, S., Robins, T. G., & Fobil, J. N. (2020). Effect of Particulate Matter Exposure on Respiratory Health of e-Waste Workers at Agbogbloshie, Accra, Ghana. *International Journal of Environmental Research and Public Health*, *17*(9), 3042.

https://doi.org/10.3390/ijerph17093042

Amoabeng Nti, A. A., Robins, T. G., Mensah, J. A., Dwomoh, D., Kwarteng, L., Takyi, S. A., Acquah, A., Basu, N., Batterman, S., & Fobil, J. N. (2021). Personal exposure to particulate matter and heart rate variability among informal electronic waste workers at Agbogbloshie: A longitudinal study. *BMC Public Health*, *21*(1), 2161. https://doi.org/10.1186/s12889-021-12241-2

Atasu, A., & Subramanian, R. (2012). Extended Producer Responsibility for E-Waste: Individual or Collective Producer Responsibility? *Production and Operations Management*, *21*(6), 1042–1059. https://doi.org/10.1111/j.1937-5956.2012.01327.x

Baldé, C. P., D'Angelo, E., Luda, V., Deubzer, O., & Kuehr, R. (2022). *Global Transboundary E-waste Flows Monitor 2022*. https://ewastemonitor.info/wp-content/uploads/2022/06/Global-TBM_webversion_june_2_pages.pdf

Berame, J. S., Lapada, A. A., Miguel, F. F., Noguera, E. C., & Alam, Z. F. (2020). Micronucleus Evaluation in Exfoliated Human Buccal Epithelium Cells among E-Waste Workers in Payatas, the Philippines. *J Health Pollut*, *10*(28), 201213. https://doi.org/10.5696/2156-9614-10.28.201213

Cao, J., Lu, B., Chen, Y., Zhang, X., Zhai, G., Zhou, G., Jiang, B., & Schnoor, J. L. (2016). Extended producer responsibility system in China improves e-waste recycling: Government policies, enterprise, and public awareness. *Renewable and Sustainable Energy Reviews*, *62*, 882–894. https://doi.org/10.1016/j.rser.2016.04.078

Carlson, K., Basu, N., Fobil, J. N., & Neitzel, R. L. (2021). Metal Exposures, Noise Exposures, and Audiometry from E-Waste Workers in Agbogbloshie, Ghana. *Int J Environ Res Public Health*, *18*(18). https://doi.org/10.3390/ijerph18189639

Chen, G., Huo, X., Luo, X., Cheng, Z., Zhang, Y., & Xu, X. (2021). E-waste polycyclic aromatic hydrocarbon (PAH) exposure leads to child gut-mucosal inflammation and adaptive immune response. *Environ Sci Pollut Res Int*, *28*(38), 53267–53281. https://doi.org/10.1007/s11356-021-14492-3

Chen, Z., Huo, X., Zhang, S., Cheng, Z., Huang, Y., & Xu, X. (2021). Relations of blood lead levels to echocardiographic left ventricular structure and function in preschool children. *Chemosphere*, *268*, 128793. https://doi.org/10.1016/j.chemosphere.2020.128793

Cheng, Z., Huo, X., Dai, Y., Lu, X., Hylkema, M. N., & Xu, X. (2020). Elevated expression of AhR and NLRP3 link polycyclic aromatic hydrocarbon exposure to cytokine storm in preschool children. *Environ Int*, *139*, 105720. https://doi.org/10.1016/j.envint.2020.105720

Chi, X., Streicher-Porte, M., Wang, M. Y. L., & Reuter, M. A. (2011). Informal electronic waste recycling: A sector review with special focus on China. *Waste Management*, *31*(4), 731–742. https://doi.org/10.1016/j.wasman.2010.11.006

Dai, Y. F., Cheng, Z. H., Zeng, Z. J., Hylkema, M. N., Faas, M. M., & Huo, X. (2022). A Targeted Lipidomic Reveals CYP450-Derived Oxylipin Linked to the Inflammatory Response by Polycyclic Aromatic Hydrocarbon Exposure in Children. *EXPOSURE AND HEALTH*. https://doi.org/10.1007/s12403-022-00503-2

Davey, B., & Walsh, E. (2019). *Decent work in the management of electrical and electronic waste (e-waste)*. 40.

Dawud, F., Takyi, S. A., Arko-Mensah, J., Basu, N., Egbi, G., Ofori-Attah, E., Bawuah, S. A., & Fobil, J. N. (2022). Relationship between Metal Exposures, Dietary Macronutrient Intake, and Blood Glucose Levels of Informal Electronic Waste Recyclers in Ghana. *Int J Environ Res Public Health*, *19*(19). https://doi.org/10.3390/ijerph191912768

Dong, J. J., Ruan, M. C., Hang, J. G., Nakayama, S. F., Jung, C. R., Kido, T., Wang, Z., Ma, C. C., & Sun, X. L. (2020). The relationship between perinatal exposure to dioxins and serum steroid hormone levels in preschool-aged children at an e-waste region in China. *Int J Hyg Environ Health*, *229*, 113580. https://doi.org/10.1016/j.ijheh.2020.113580

Dutta, D., Rautela, R., Gujjala, L. K. S., Kundu, D., Sharma, P., Tembhare, M., & Kumar, S. (2023). A review on recovery processes of metals from E-waste: A green perspective. *Science of The Total Environment*, *859*, 160391. https://doi.org/10.1016/j.scitotenv.2022.160391

EPA. (2015, August 19). *Learn about Polychlorinated Biphenyls* [Other Policies and Guidance]. https://www.epa.gov/pcbs/learn-about-polychlorinated-biphenyls

Fischer, D., Seidu, F., Yang, J., Felten, M. K., Garus, C., Kraus, T., Fobil, J. N., & Kaifie, A. (2020). Health Consequences for E-Waste Workers and Bystanders—A Comparative Cross-Sectional Study. *International Journal of Environmental Research and Public Health*, *17*(5), Article 5. https://doi.org/10.3390/ijerph17051534

Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). *The Global E-waste Monitor 2020*.

Goyer, R. A. (1995). Nutrition and metal toxicity. *The American Journal of Clinical Nutrition*, *61*(3 Suppl), 646S-650S. https://doi.org/10.1093/ajcn/61.3.646S

Grant, K., Goldizen, F. C., Sly, P. D., Brune, M.-N., Neira, M., van den Berg, M., & Norman, R. E. (2013). Health consequences of exposure to e-waste: A systematic review. *The Lancet Global Health*, *1*(6), e350–e361. https://doi.org/10.1016/S2214-109X(13)70101-3

Gravel, S., Lavoué, J., Bakhiyi, B., Lavoie, J., Roberge, B., Patry, L., Bouchard, M. F., Verner, M. A., Zayed, J., & Labrèche, F. (2020). Multi-exposures to suspected endocrine disruptors in electronic waste recycling workers: Associations with thyroid and reproductive hormones. *Int J Hyg Environ Health*, *225*, 113445. https://doi.org/10.1016/j.ijheh.2019.113445

Guo, C., Qian, Y., Yan, L., Li, Z., Liu, H., Li, X., Wang, Z., Zhu, X., Wang, Z., Wang, J., & Wei, Y. (2021). The changes of essential trace elements in residents from an e-waste site and the relationships between elements and hormones of the hypothalamic-pituitary-thyroid (HPT) axis. *Ecotoxicol Environ Saf*, *222*, 112513. https://doi.org/10.1016/j.ecoenv.2021.112513

Guo, C., Wei, Y., Yan, L., Li, Z., Qian, Y., Liu, H., Li, Z., Li, X., Wang, Z., & Wang, J. (2020). Rare earth elements exposure and the alteration of the hormones in the hypothalamic-pituitary-thyroid (HPT) axis of the residents in an e-waste site: A cross-sectional study. *Chemosphere*, *252*, 126488. https://doi.org/10.1016/j.chemosphere.2020.126488

Guo, L. C., Liu, T., Yang, Y., Yu, S., Gao, Y., Huang, W., Xiao, J., Ma, W., Rutherford, S., & Zhang, Y. (2020). Changes in thyroid hormone related proteins and gene expression induced by polychlorinated biphenyls and halogen flame retardants exposure of children in a Chinese e-waste recycling area. *Sci Total Environ*, *742*, 140597. https://doi.org/10.1016/j.scitotenv.2020.140597

Guo, L. C., Lv, Z., Zhu, T., He, G., Hu, J., Xiao, J., Liu, T., Yu, S., Zhang, J., Zhang, H., & Ma, W. (2023). Associations between serum polychlorinated biphenyls, halogen flame retardants, and renal function indexes in residents of an e-waste recycling area. *Sci Total Environ*, *858*(Pt 1), 159746. https://doi.org/10.1016/j.scitotenv.2022.159746

Hashmi, M. Z., Chen, K., Khalid, F., Yu, C., Tang, X., Li, A., & Shen, C. (2022). Forty years studies on polychlorinated biphenyls pollution, food safety, health risk, and human health in an e-waste recycling area from Taizhou city, China: A review. *Environmental Science and Pollution Research International*, *29*(4), 4991–5005. https://doi.org/10.1007/s11356-021-17516-0

Huang, X., Xu, X., Dai, Y., Cheng, Z., Zheng, X., & Huo, X. (2020). Association of prenatal exposure to PAHs with anti-Müllerian hormone (AMH) levels and birth outcomes of newborns. *Sci Total Environ*, *723*, 138009. https://doi.org/10.1016/j.scitotenv.2020.138009

Iavicoli, I., Fontana, L., & Bergamaschi, A. (2009). The effects of metals as endocrine disruptors. *Journal of Toxicology and Environmental Health. Part B, Critical Reviews*, *12*(3), 206–223. https://doi.org/10.1080/10937400902902062

Issah, I., Arko-Mensah, J., Rozek, L. S., Rentschler, K., Agyekum, T. P., Dwumoh, D., Batterman, S., Robins, T. G., & Fobil, J. N. (2022). Association between global DNA methylation (LINE-1) and occupational particulate matter exposure among informal electronic-waste recyclers in Ghana. *Int J Environ Health Res*, *32*(11), 2406–2424. https://doi.org/10.1080/09603123.2021.1969007

Issah, I., Arko-Mensah, J., Rozek, L. S., Zarins, K. R., Agyekum, T. P., Dwomoh, D., Basu, N., Batterman, S., Robins, T. G., & Fobil, J. N. (2021). Global DNA (LINE-1) methylation is associated with lead exposure and certain job tasks performed by electronic waste workers. *Int Arch Occup Environ Health*, *94*(8), 1931–1944. https://doi.org/10.1007/s00420-021-01733-8

Issah, I., Arko-Mensah, J., Rozek, L. S., Zarins, K. R., Dwomoh, D., Agyekum, T. P., Basu, N., Batterman, S., Robins, T. G., & Fobil, J. N. (2022). Association between toxic and essential metals in blood and global DNA methylation among electronic waste workers in Agbogbloshie, Ghana. *Environmental Science and Pollution Research International*, *29*(48), 72946–72956. https://doi.org/10.1007/s11356-022-20954-z

Jaiswal, A., Samuel, C., Patel, B. S., & Kumar, M. (2015). Go Green with WEEE: Eco-friendly Approach for Handling E- waste. *Procedia Computer Science*, *46*, 1317–1324. https://doi.org/10.1016/j.procs.2015.01.059

Jangre, J., Prasad, K., & Patel, D. (2022). Analysis of barriers in e-waste management in developing economy: An integrated multiple-criteria decision-making approach. *Environmental Science and Pollution Research International*, *29*(48), 72294–72308. https://doi.org/10.1007/s11356-022-21363-y

Johanna Treblin. (2013, May 27). *Informal Recycling of E-waste a Serious Problem, Expert Says—Our World*. Our World. https://ourworld.unu.edu/en/informal-recycling-of-e-waste-a-serious-problem-expert-says

Jon Hurdle. (2023, February 28). As Millions of Solar Panels Age Out, Recyclers Hope to Cash In. *Yale E360*. https://e360.yale.edu/features/solar-energy-panels-recycling

Kêdoté, N. M., Sopoh, G. E., Tobada, S. B., Darboux, A. J., Fonton, P., Sanon Lompo, M. S., & Fobil, J. (2022). Perceived Stress at Work and Associated Factors among E-Waste Workers in French-Speaking West Africa. *Int J Environ Res Public Health*, *19*(2). https://doi.org/10.3390/ijerph19020851

Kim, S. S., Xu, X., Zhang, Y., Zheng, X., Liu, R., Dietrich, K. N., Reponen, T., Xie, C., Sucharew, H., Huo, X., & Chen, A. (2020). Birth outcomes associated with maternal exposure to metals from informal electronic waste recycling in Guiyu, China. *Environ Int*, *137*, 105580. https://doi.org/10.1016/j.envint.2020.105580

Kuang, H., Li, Y., Li, L., Ma, S., An, T., & Fan, R. (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. https://doi.org/10.1016/j.scitotenv.2022.156595

Lebbie, T. S., Moyebi, O. D., Asante, K. A., Fobil, J., Brune-Drisse, M. N., Suk, W. A., Sly, P. D., Gorman, J., & Carpenter, D. O. (2021). E-Waste in Africa: A Serious Threat to the Health of Children. *International Journal of Environmental Research and Public Health*, *18*(16), 8488. https://doi.org/10.3390/ijerph18168488

Li, Z., Guo, C., Li, X., Wang, Z., Wu, J., Qian, Y., & Wei, Y. (2020). Associations between metal exposure and global DNA methylation in potentially affected people in E-Waste recycling sites in Taizhou City, China. *The Science of the Total Environment*, *711*, 135100. https://doi.org/10.1016/j.scitotenv.2019.135100

Li, Z., Li, X., Qian, Y., Guo, C., Wang, Z., & Wei, Y. (2020). The sustaining effects of e-waste-related metal exposure on hypothalamus-pituitary-adrenal axis reactivity and oxidative stress. *Science of The Total Environment*, *739*, 139964. https://doi.org/10.1016/j.scitotenv.2020.139964

Li, Z., Liu, H., Qian, Y., Li, X., Guo, C., Wang, Z., & Wei, Y. (2020). Influence of metals from e-waste dismantling on telomerelength and mitochondrial DNA copy number in people living near recycling sites. *Environment International*, *140*, 105769. https://doi.org/10.1016/j.envint.2020.105769

Li, Z., Wang, Z., Xue, K., Wang, Z., Guo, C., Qian, Y., Li, X., & Wei, Y. (2021). High concentration of blood cobalt is associated with the impairment of blood-brain barrier permeability. *Chemosphere*, *273*, 129579. https://doi.org/10.1016/j.chemosphere.2021.129579

Lin, B. G., Chen, C. R., Chen, X. C., Qiao, J., Yan, Q. X., Yang, P., Chen, W. L., Li, L. Z., Qiu, P. C., Ding, C., Huang, D. J., & Yu, Y. J. (2021). Effects of organochlorine exposure on male reproductive disorders in an electronic waste area of South China. *Environ Int*, *147*, 106318. https://doi.org/10.1016/j.envint.2020.106318

Luo, X., Huo, X., Zhang, Y., Cheng, Z., Chen, S., & Xu, X. (2021). Increased intestinal permeability with elevated peripheral blood endotoxin and inflammatory indices for e-waste lead exposure in children. *Chemosphere*, *279*, 130862. https://doi.org/10.1016/j.chemosphere.2021.130862

Misra, N. R., Kumar, S., & Jain, A. (2021). A Review on E-waste: Fostering the Need for Green

Electronics. *2021 International Conference on Computing, Communication, and Intelligent Systems (ICCCIS)*, 1032–1036. https://doi.org/10.1109/ICCCIS51004.2021.9397191

Neitzel, R. L., Sayler, S. K., Arain, A. L., & Nambunmee, K. (2020). Metal Levels, Genetic Instability, and Renal Markers in Electronic Waste Workers in Thailand. *Int J Occup Environ Med*, *11*(2), 72–84. https://doi.org/10.34172/ijoem.2020.1826

Ngo, H. T. T., Liang, L., Nguyen, D. B., Doan, H. N., & Watchalayann, P. (2021). Blood heavy metals and DNA damage among children living in an informal E-waste processing area in Vietnam. *HUMAN AND ECOLOGICAL RISK ASSESSMENT*, *27*(2), 541–559. https://doi.org/10.1080/10807039.2020.1736985

OECD. (2006). *Fact Sheet: Extended Producer Responsibility*. https://www.oecd.org/env/waste/factsheetextendedproducerresponsibility.htm

Parvez, S. M., Jahan, F., Brune, M.-N., Gorman, J. F., Rahman, M. J., Carpenter, D., Islam, Z., Rahman, M., Aich, N., Knibbs, L. D., & Sly, P. D. (2021). Health consequences of exposure to e-waste: An updated systematic review. *The Lancet Planetary Health*, *5*(12), e905–e920. https://doi.org/10.1016/S2542-5196(21)00263-1

Patil, R. A., & Ramakrishna, S. (2020). A comprehensive analysis of e-waste legislation worldwide. *Environmental Science and Pollution Research*, *27*(13), 14412–14431. https://doi.org/10.1007/s11356-020-07992-1

Paul T. Anastas & Julie B. Zimmerman. (2003). Design Through the 12 Principles of Green Engineering. *Environmental Science & Technology*, *37*(5), 94A-101A. https://doi.org/10.1021/es032373g

Peter Yeung. (2019, May 29). The Rich World's Electronic Waste, Dumped in Ghana. *Bloomberg.Com*. https://www.bloomberg.com/news/articles/2019-05-29/the-rich-world-s-electronic-waste-dumped-in-ghana

Qin, Q., Xu, X., Dai, Q., Ye, K., Wang, C., & Huo, X. (2019). Air pollution and body burden of persistent organic pollutants at an electronic waste recycling area of China. *Environmental Geochemistry and Health*, *41*(1), 93–123. https://doi.org/10.1007/s10653-018-0176-y

Shi, L. L., Wang, M. Q., Nakayama, S. F., Jung, C.-R., Wang, Y. H., Dong, J. J., Ma, C. C., Kido, T., Sun, X. L., & Feng, H. (2020). The association between dioxins and steroid hormones in general adult males: A cross-sectional study in an e-waste region of China. *Environmental Science and Pollution Research*, *27*(21), 26511–26519. https://doi.org/10.1007/s11356-020-09086-4

Shittu, O. S., Williams, I. D., & Shaw, P. J. (2021). Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. *Waste Management*, *120*, 549–563. https://doi.org/10.1016/j.wasman.2020.10.016

Soetrisno, F. N., & Delgado-Saborit, J. M. (2020). Chronic exposure to heavy metals from informal e-waste recycling plants and children's attention, executive function and academic performance. *Sci Total Environ*, *717*, 137099. https://doi.org/10.1016/j.scitotenv.2020.137099

Song, S., Duan, Y., Zhang, T., Zhang, B., Zhao, Z., Bai, X., Xie, L., He, Y., Ouyang, J.-P., Huang, X., & Sun, H. (2019). Serum concentrations of bisphenol A and its alternatives in elderly population living around e-waste recycling facilities in China: Associations with fasting blood glucose. *Ecotoxicology and Environmental Safety*, *169*, 822–828. https://doi.org/10.1016/j.ecoenv.2018.11.101

Tahir, M., Rehman, M. Y. A., & Malik, R. N. (2021). Heavy metal-associated oxidative stress and glutathione S-transferase polymorphisms among E-waste workers in Pakistan. *Environ Geochem Health*, *43*(11), 4441–4458. https://doi.org/10.1007/s10653-021-00926-x

Tang, J., Ma, S., Hu, X., Lin, M., Li, G., Yu, Y., & An, T. (2023). Handwipes as indicators to assess organophosphate flame retardants exposure and thyroid hormone effects in e-waste dismantlers. *J Hazard Mater*, *443*(Pt B), 130248. https://doi.org/10.1016/j.jhazmat.2022.130248

UNEP. (2009). *Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling—From E-Waste to Resources*. https://wedocs.unep.org/20.500.11822/33112

United States Department of State. (2023, April 20). *Basel Convention on Hazardous Wastes*. https://www.state.gov/key-topics-office-of-environmental-quality-and-transboundary-issues/basel-convention-on-hazardous-wastes/

Upadhyay, K., Viramgami, A., Pagdhune, A., Balachandar, R., & Sarkar, K. (2021). Hematological and cardiovascular effects of chronic low level lead exposure: A study on e-waste recyclers. *CLINICAL EPIDEMIOLOGY AND GLOBAL HEALTH*, *9*, 269–274. https://doi.org/10.1016/j.cegh.2020.09.009

Wachinou, A. P., Kêdoté, N. M., Padonou, G., Adè, S., Darboux, J., Tohi, M., Fiogbé, A., Fobil, J., & Agodokpessi, G. (2022). Respiratory Disorders Related to e-Waste Exposure among Workers in the Informal Sector in a Sub-Saharan African City: An Exposed Nonexposed Study. *Pulmonary Medicine*, *2022*, e9968897. https://doi.org/10.1155/2022/9968897

Wang, H., Huang, P., Zhang, R., Feng, X., Tang, Q., Liu, S., Wen, F., Zeng, L., Liu, Y., Wang, T., & Ma, L. (2021). Effect of lead exposure from electronic waste on haemoglobin synthesis in children. *Int Arch Occup Environ Health*, *94*(5), 911–918. https://doi.org/10.1007/s00420-020-01619-1

Wang, K., Qian, J., & Liu, L. (2020). Understanding Environmental Pollutions of Informal E-Waste Clustering in Global South via Multi-Scalar Regulatory Frameworks: A Case Study of Guiyu Town, China. *International Journal of Environmental Research and Public Health*, *17*(8), Article 8. https://doi.org/10.3390/ijerph17082802

Wang, Q., Xu, X., Zeng, Z., Hylkema, M. N., Cai, Z., & Huo, X. (2020). PAH exposure is associated with enhanced risk for pediatric dyslipidemia through serum SOD reduction. *Environ Int*, *145*, 106132. https://doi.org/10.1016/j.envint.2020.106132

Wang, Q., Xu, X., Zeng, Z., Zheng, X., Ye, K., & Huo, X. (2020). Antioxidant alterations link polycyclic aromatic hydrocarbons to blood pressure in children. *Sci Total Environ*, *732*, 138944. https://doi.org/10.1016/j.scitotenv.2020.138944

Wang, Y., Wang, Q., Zhou, L., Zeng, Z., Zhao, C., You, L., Lu, X., Liu, X., Ouyang, R., Wang, Y., Xu, X., Tian, X., Guo, Y., Huo, X., & Xu, G. (2022). Metabolomics insights into the prenatal exposure effects of polybrominated diphenyl ethers on neonatal birth outcomes. *Sci Total Environ*, *836*, 155601. https://doi.org/10.1016/j.scitotenv.2022.155601

Wang, Z., Sun, Y., Dong, J. J., Shi, L. L., Nakayama, S. F., Kido, T., Jung, C.-R., Ma, C., Feng, H., Hang,

J. G., & Sun, X. L. (2022). Relationship between dioxins and steroid hormone in 6-year-olds: A follow-up study in an e-waste region of China. *Chemosphere*, *296*, 134018. https://doi.org/10.1016/j.chemosphere.2022.134018

Wang, Z., Xue, K., Wang, Z., Zhu, X., Guo, C., Qian, Y., Li, X., Li, Z., & Wei, Y. (2022). Effects of e-waste exposure on biomarkers of coronary heart disease (CHD) and their associations with level of heavy metals in blood. *Environmental Science and Pollution Research International*, *29*(33), 49850–49857. https://doi.org/10.1007/s11356-021-15656-x

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., & Boni, H. (2005). Global perspectives on e-waste. *Environmental Impact Assessment Review*, *25*(5), 436–458. https://doi.org/10.1016/j.eiar.2005.04.001

World Economic Forum, P. for A. the C. E. (PACE). (2019). *A New Circular Vision for Electronics: Time for a Global Reboot*. https://wedocs.unep.org/20.500.11822/32762

Wu, C. M. L., Yu, D. Q., Law, C. M. T., & Wang, L. (2004). Properties of lead-free solder alloys with rare earth element additions. *Materials Science and Engineering: R: Reports*, *44*(1), 1–44. https://doi.org/10.1016/j.mser.2004.01.001

Wu, Q., Leung, J. Y. S., Du, Y., Kong, D., Shi, Y., Wang, Y., & Xiao, T. (2019). Trace metals in e-waste lead to serious health risk through consumption of rice growing near an abandoned e-waste recycling site: Comparisons with PBDEs and AHFRs. *Environmental Pollution (Barking, Essex: 1987)*, *247*, 46–54. https://doi.org/10.1016/j.envpol.2018.12.051

Xu, L., Huo, X., Liu, Y., Zhang, Y., Qin, Q., & Xu, X. (2020). Hearing loss risk and DNA methylation signatures in preschool children following lead and cadmium exposure from an electronic waste recycling area. *Chemosphere*, *246*, 125829. https://doi.org/10.1016/j.chemosphere.2020.125829

Xue, K., Qian, Y., Wang, Z., Guo, C., Wang, Z., Li, X., Li, Z., & Wei, Y. (2021). Cobalt exposure increases the risk of fibrosis of people living near E⁻waste recycling area. *Ecotoxicol Environ Saf*, *215*, 112145. https://doi.org/10.1016/j.ecoenv.2021.112145

Yanzhu Zhang. (2018, March 29). *Informal vs formal recycling: The dilemma of e-waste management*.

University of Oxford.
https://www.bsg.ox.ac.uk/blog/informal-vs-formal-recycling-dilemma-e-waste-management

Young-hye Na. (2019, December 18). Free of Heavy Metals, New Battery Design Could Alleviate Environmental Concerns. *IBM Research Blog*. https://www.ibm.com/blogs/research/2019/12/heavy-metal-free-battery/

Zeng, X., Gong, R., Chen, W.-Q., & Li, J. (2016). Uncovering the Recycling Potential of "New" WEEE in China. *Environmental Science & Technology*, *50*(3), 1347–1358. https://doi.org/10.1021/acs.est.5b05446

Zeng, X., Xu, C., Xu, X., Huang, Y., Wang, Q., & Huo, X. (2022). Combined toxicity of air pollutants related to e-waste on inflammatory cytokines linked with neurotransmitters and pediatric behavioral problems. *Ecotoxicol Environ Saf*, *239*, 113657. https://doi.org/10.1016/j.ecoenv.2022.113657

Zeng, X., Xu, C., Xu, X., Zhang, Y., Huang, Y., & Huo, X. (2021). Elevated lead levels in relation to low serum neuropeptide Y and adverse behavioral effects in preschool children with e-waste exposure. *Chemosphere*, *269*, 129380. https://doi.org/10.1016/j.chemosphere.2020.129380

Zeng, X., Xu, X., Boezen, H. M., & Huo, X. (2016). Children with health impairments by heavy metals in an e-waste recycling area. *Chemosphere*, *148*, 408–415. https://doi.org/10.1016/j.chemosphere.2015.10.078

Zeng, X., Zeng, Z., Wang, Q., Liang, W., Guo, Y., & Huo, X. (2022). Alterations of the gut microbiota and metabolomics in children with e-waste lead exposure. *J Hazard Mater*, *434*, 128842. https://doi.org/10.1016/j.jhazmat.2022.128842

Zeng, Z., Xu, X., Wang, Q., Zhang, Z., Meng, P., & Huo, X. (2022). Maternal exposure to atmospheric PM(2.5) and fetal brain development: Associations with BAI1 methylation and thyroid hormones. *Environ Pollut*, *308*, 119665. https://doi.org/10.1016/j.envpol.2022.119665

Zeng, Z., Xu, X., Zhu, Y., Wang, Q., Zhang, Y., & Huo, X. (2022). Pb and Cd exposure linked with Il-10 and Il-13 gene polymorphisms in asthma risk relevant immunomodulation in children.

Chemosphere, *294*, 133656. https://doi.org/10.1016/j.chemosphere.2022.133656

Zhang, S., Huo, X., Li, M., Hou, R., Cong, X., & Xu, X. (2020). Oral antimicrobial activity weakened in children with electronic waste lead exposure. *Environ Sci Pollut Res Int*, *27*(13), 14763–14770. https://doi.org/10.1007/s11356-020-08037-3

Zhang, W.-H., Wu, Y.-X., & Simonnot, M. O. (2012). Soil Contamination due to E-Waste Disposal and Recycling Activities: A Review with Special Focus on China. *Pedosphere*, *22*(4), 434–455. https://doi.org/10.1016/S1002-0160(12)60030-7

Zhang, Y., Huo, X., Lu, X., Zeng, Z., Faas, M. M., & Xu, X. (2020). Exposure to multiple heavy metals associate with aberrant immune homeostasis and inflammatory activation in preschool children. *Chemosphere*, *257*, 127257. https://doi.org/10.1016/j.chemosphere.2020.127257

Zhao, L., Lu, Y., Zhu, H., Cheng, Z., Wang, Y., Chen, H., Yao, Y., Zhang, J., Li, X., Sun, Z., Zhang, C., & Sun, H. (2022). E-waste dismantling-related occupational and routine exposure to melamine and its derivatives: Estimating exposure via dust ingestion and hand-to-mouth contact. *Environment International*, *165*, 107299. https://doi.org/10.1016/j.envint.2022.107299

Zheng, X., Xu, X., Lu, F., Wang, Q., Zeng, Z., & Huo, X. (2021). High serum IgG subclass concentrations in children with e-waste Pb and Cd exposure. *Sci Total Environ*, *764*, 142806. https://doi.org/10.1016/j.scitotenv.2020.142806

Zhou, Y., Lü, S. M., Xiao, J. P., Liu, T., Ma, W. J., & Guo, L. C. (2020). Effects of Polybrominated Diphenyl Ethers on the Human Body Exposure in E-Waste Dismantling Region. *Fa Yi Xue Za Zhi*, *36*(4), 453–460. https://doi.org/10.12116/j.issn.1004-5619.2020.04.004

Zhu, X., Li, Z., Guo, C., Wang, Z., Wang, Z., Li, X., Qian, Y., & Wei, Y. (2021). Risk of neurodegeneration among residents of electronic waste recycling areas. *Ecotoxicol Environ Saf*, *230*, 113132. https://doi.org/10.1016/j.ecoenv.2021.113132