Environmental Health Impacts of Informal Electronic Waste Recycling

by

Aubrey Leigh Arain

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Environmental Health Sciences)
in The University of Michigan
2019

Doctoral Committee:

Associate Professor Richard L. Neitzel, Chair
Assistant Professor Jesse Austin-Breneman
Associate Professor Veronica Berrocal
Professor Olivier Jolliet

Aubrey Leigh Arain

AubreyLL@umich.edu

ORCID iD: 0000-0002-7654-0135

Dedication

To my family:

To my Husband, who embarked on this journey beside me, unwavering in his support.

To my Dad, who always encouraged me to wander.

To my Mom, who never said “no” to a dream.

To my Brother, who lead the way, perhaps without realizing that I was following.

Acknowledgements

After 6 years at the University of Michigan, my training in graduate school is now complete. Throughout this long and, at times, arduous journey, I have been fortunate enough to partake in many types of new and exciting experiences. From conferences to research trips around the globe, I have interacted with people from all different walks of life and have learned far more about public health than training inside of a brick and mortar building could have ever afforded. These experiences would never have been possible without the help of my mentors, family, and friends who supported my efforts.

During my time in the Department of Environmental Health Sciences, I have been inspired to seek knowledge, discipline, and ambition. I have grown in every aspect of my professional life, as well as personally. I have experienced awe in the presence of talent around me, and I have struggled to find my own footing. I have been challenged, and I have met those challenges, if not always on the first try. The greatest trial during these four years came only one month into my Ph.D. program. I lost my mother very, very unexpectedly. I received an enormous amount of support and understanding from fellow students, faculty and staff as I pushed forward with the program through my grief. I am eternally grateful for the space I was given to heal.

First and foremost, I would like to thank God, who blessed me with the opportunity to purse a Ph.D. Through Him I found the strength and courage necessary to complete my program.

Next, I would like to sincerely thank my advisor, Dr. Richard Neitzel, whose expertise, guidance, and passion for research have been paramount to my success. Dr. Neitzel taught me that the world of occupational health and safety is far more than risk and exposure science. It has deep roots of social justice, and worker protections are never guaranteed. Lab members joke that Dr. Neitzel never sleeps, as an email is just as likely to get an immediate response at 11 PM as 4 AM. His dedication to his students, and his desire for us to succeed, is tangible. I feel truly fortunate to have such an advisor.

I would like to thank my committee members, who have challenged me to think differently, and have worked assiduously to mentor me in their different areas of expertise. Dr. Olivier Jolliet assisted me in developing a research question that could be answered using Life Cycle Assessment methods and then helped me to develop the model. Furthermore, he taught me the importance of being systematic and meticulous in research. Dr. Jesse Austin-Breneman has consistently pushed me to understand my research on a deeper level, particularly the significance and implications of my work. In addition, he encouraged me to design my research in a new way, testing linkages between observation and effect. Finally, Dr. Veronica Berrocal asked perceptive questions and gave thoughtful counsel, helping me to better understand the nuances of various methods and to account for them in my work.

My dissertation data was derived from field visits to Thailand and Chile. In each country, a whole team of people working together on a larger, parent e-waste project assisted in research design, data collection, and logistics. I am grateful to have had the opportunity to work with each and every one of them. One of our collaborators in Chile, Dr. Pablo Rudolph-Ruiz, served as a mentor in the importance of public engagement of researchers.

I have made 3 trips to Thailand over these four years, and along the way I developed very special bonds. Community health volunteers who lived in the research site not only assisted in recruitment, transportation, and logistics of the data collection process, they introduced me to foods from their homes and gardens, laughed with me despite language barriers, and shared their culture with me. They will always hold a special place in my heart and I hope to meet them again. Also in Thailand, our collaborators, Dr. Kowit Nambunmee of Mae Fah Luang University and Siripond “Kie” Jindaphong, were gracious hosts in addition to dedicated partners. Finally, I would like to sincerely thank research participants in each country, without whom this work would not have been possible.

Thank you to Dr. Roland Hischier of Empa, who helped me immensely in the development of the life cycle inventory for Chapter 3. Dr. Hischier gave recommendations based on his previous work modelling WEEE in the formal sector, and additionally modelled the recycling of plastic from e-waste using industry secrets for use in our analysis. Dr. Brian Gullet, EPA, answered the phone when Dr. Jolliet and myself called him without notice to ask a very specific question about a paper he published 10 years before. Dr. Gullet graciously referred to his data and provided us with calculations to use in the loss of copper in burning of cables for Chapter 3.

I have received support during my PhD program from numerous sources, allowing me to focus my energy on research. Tuition and stipend support came from the National Institute of Health, the National Institute of Occupational Safety and Health, and Rackham Graduate School. Research grants helped fund data collection and analysis: Center for Occupational Health and Safety, Marans/Chen Fellowship, School of Public Health Office of Public Health, Center for the Education of Women, Center for Southeast Asian Studies, University of Michigan International Institute, and Rackham Graduate School.

Finally, I would like to thank my family and friends, who have supported me unconditionally over the past six years. In particular, my husband, Mansoor Arain, has been the keystone in my success. He has encouraged me, pushed me, and inspired me to do better. He has

served as a sounding board for ideas, assisted as a reviewer of my work at times, and has listened to me practice presentations. More importantly, he has served as a source of comfort and allowed me to pursue my passion over the last four years.

Preface

The basis for this research originally stemmed from my passion for the environment and research designed to protect its quality and integrity for future generations. Of particular interest is the notion of informal economies, where disadvantaged populations are employed in activities that are frequently degrading of natural resources and undermine environmental quality standards and enforcement, being demonized by media sources as creating environmental catastrophes. As real as the pollution may be, damage from informal sectors often pales in comparison to large formal industries, for example oil and gas. The lack of social and occupational security benefits from an informal industry makes it easier for the media and the world to disparage informal workers. Talked about far less frequently is the immense history of socio-political contexts that would explain the circumstances and decisions of informal workers. These conversations are the ones that are needed to reach the revelation that elimination of workers in the informal economy is not the solution to environmental devastation.

During my four years in my Ph.D. program, I came to love the field of occupational health and science. There is much overlap in the injustice between occupational and environmental health. Both healthy environments and healthy workers are often a position of privilege in a global context. The foundation I have built in my graduate school experience will allow me to continue forward on work that unites these two spheres of interest, searching for solutions that optimize each.

Table of Contents

List of Tables

List of Figures

List of Appendices

List of Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AWQC	Ambient Water Quality Criterion
BEI	Biological Exposure Index
CHMS	Canadian Health Measures Survey
CRT	Cathode Ray Tube
EHS	Environmental Health Sciences
EOL	End of Life
EPA	Environmental Protection Agency
FU	Functional Unit
IRR	Incidence Rate Ratio
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LOD	Limit of Detection
MFA	Material Flow Analysis
ML	Maximum Level
NHANES	National Health and Nutrition Examination Survey
NIHL	Noise-Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health

OR	Odds Ratio
OSHA	Occupational Safety and Health Administration
PBDE	Polybrominated Diphenyl Ethers
PBZ	Personal Breathing Zone
PCB	Printed Circuit Board
PMTDI	Permissible Maximum Tolerable Daily Intake
PPE	Personal Protective Equipment
PPP	Purchasing Power Parity
REL	Recommended Exposure Limit
TLV	Threshold Limit Value
TUIL	Tolerable Upper Intake Limit
TWA	Time Weighted Average
TWH	Total Worker Health
USD	United States Dollar

Abstract

Electronic waste, “E-waste”, is the fastest growing waste stream globally. Informal e-waste recycling lacks the policy and regulatory controls found in formal industry, creating health hazards for workers and communities, while potentially achieving higher recovery rates of raw materials and related reductions in impacts. This dissertation evaluated routes of exposure to metals, physical hazards faced by workers, material and economic flows, and environmental and human health damages, through the lens of Total Worker Health (TWH). The research described took place in informal e-waste recycling communities in Thailand and Chile, countries with different cultural contexts and recycling paradigms.

Following the introduction in Chapter 1, Chapter 2 examined and compared metal levels in a variety of environmental samples, surface dust, air, and human biomarkers. Concentrations of metals in environmental samples were elevated. Surface wipe samples from Thailand showed no significant difference in metal concentrations between surfaces used for food and work, while there was a difference in Chile. Despite having higher overall concentrations of metals in wipe samples, workers in Chile had lower concentrations of metal biomarkers than workers and non-workers in Thailand. Results from an application of the Method of Triads showed that surface wipes generally had the highest validity coefficients of the various measures evaluated.

Chapter 3 evaluated the physical hazards of e-waste recycling. No workers were exposed above the recommended occupational limit for noise of 85 dBA. However, a portion of workers had audiograms indicative of noise-induced hearing loss. Sixty percent of workers in each

country experienced ≥1 work injury in the previous 6 months. Analysis of injury risk factors using survey data and a novel semi-quantitative video analysis indicated high frequencies of ergonomic stressors and working near sharp objects in both countries. Logistic regressions in Thailand showed that odds of injury were greater among workers who reported more frequent noise and regular use of personal protective equipment. In Chile, buying/selling of e-waste was associated with lower odds of injury. Poisson regressions showed that older and more educated workers in Thailand had a lower injury incidence rate ratio (IRR). In Chile, older, more educated workers, report of a dangerous task, increased frequency in the use of cotton gloves, repetitive arm motion, and lifting of <20 pounds had a higher IRR.

Chapter 4 combined material flow analysis (MFA) and life cycle assessment (LCA) methods to analyze the quantitative flow of materials, economic benefits, and human and environmental impacts of informal e-waste recycling. Four e-waste products were selected for the MFA in a Thai community and then fed into a LCA to estimate net avoided emissions. One village processed ~40,000 kg of e-waste monthly, worth a net value added of 157,000 THB (~$5,000). Recycling in one village avoided 0.2 Disability-Adjusted Life Years, 60,000 kg of CO_2 equivalents, and nearly 400,000 megajoules each month. Dismantling of e-waste by informal e-waste workers with downstream processes (e.g., recovery of dangerous, precious, and trace materials) completed by more formalized operations may be advantageous for both sectors. Finally, Chapter 5 provides overall conclusions and discussion.

This dissertation yielded important information on how to protect informal e-waste worker and community health. Exposures to metals occurred during both work and non-work activities, and the participating workers experienced a high rate of injury, affecting health and economic well-being. Short-term economic benefits may be out-weighed by long-term ecosystem damages.

Chapter 1 : Introduction

1.1 Introduction to informal e-waste recycling

Electronics play a prominent role in modern society and will continue to grow as an integral part of daily life as technology continues to develop [1], [2]. Increasing consumer demand, availability of new technologies, incorporation of existing technology into new products, shortened product lifetimes, and a growing global consumer base all contribute to increased production of electronics and electrical equipment. Although technology has the potential to improve human welfare and experiences, the growing number of electronics comes with a growing number of discarded products. Without the policy, technological, or economic structures necessary to sustainably dispose of or recycle these products, the world has found itself in a quandary over electronic waste.

Electronics and electrical equipment that have reached the end of their useable life, collectively known as “e-waste”, includes products such as personal and large appliances, communication and information technology, medical equipment, parts of vehicles, and all other products and components containing electrical circuitry [2]. E-waste is the fastest growing waste stream on earth with an estimated 44.7 million metric tons generated globally in 2014 alone [3]. The amount of e-waste generated annually per person is expected to increase from 5.8 kg/person in 2014 to 6.8 kg/person in 2021 [3]. This increase is multiplicative in effect when we consider the growing global population. Policy infrastructure, consumer behavior, and producer responsibility in the electronics industry have lagged behind technological innovation. As a result, much of the e-waste generated each year is disposed of in a landfill.

The lack of sustainable end-of-life management of electronics results in negative environmental consequences. The failure to recover secondary materials from landfilled e-waste results in a larger need for extraction of primary materials, leaching of hazardous materials into the environment, and increases the volume of waste in landfills [1]. Beyond the socio-political limitations needed to improve electronic recycling systems, there is a need for technological development and economic investments in recycling infrastructure. The large mix of elements contained within e-waste, many of which are hazardous, combined with the diverse array of electronic products and the physical properties of different components makes the separation and recovery of materials difficult [4]. To maximize recycling efficiency, new methods of sorting, shredding, separating, and recovering e-waste products and materials are needed. Recycling methods need to be updated regularly to keep up with changes in technology and manufacturing methods [5].

Electronics contain an array of scarce and valuable materials that can be recovered and sold in secondary markets to be incorporated into new goods. Metals like gold, silver, copper, steel, and palladium, as well as plastics, trace elements, and other materials can be recovered from e-waste [6], [7]. In some cases, particularly with metals like gold and copper, it is more economically efficient to recover and process secondary materials than to produce primary materials through the extraction of virgin materials [8]. The formal, organized recycling of electronics is expensive, prompting many high-income countries to export a portion of collected e-waste to low- and middle-income countries despite a ban on this practice under the United Nations Basel Convention [6], [9]. It has been estimated that only 20% of e-waste generated in high-income countries is collected and recycled in the formal sector, and 76% is landfilled, traded, or recycled in substandard conditions [10]. Of the total amount of e-waste recovered in high-income countries, approximately 80% is shipped, frequently illegally, to low- and middle-income countries [11]. Recycling in these destinations is often performed by workers in the informal sector with use of rudimentary methods to recover materials [12].

While e-waste represents an important source of income in lower-income parts of the globe, it also contains chemicals harmful to the environment. Persistent organic pollutants, such as polychlorinated biphenyls (PCBs) and some polybrominated diphenyl ethers (PBDEs), as well as heavy metals like cadmium, lead, and copper are released during the recycling process and are of great concern to human and environmental health [13]-[15]. Proper equipment and recycling technology is often lacking in the informal sector, along with health and environmental regulations [16]. Therefore, workers recover materials using primitive methods, including the burning of wires to remove plastic coating, dissolving circuit boards in acid baths to retrieve precious metals, and using homemade tools to disassemble products in inferior work settings [17]. The lack of proper controls results in the release of toxicants from e-waste, contaminating humans and the local environment.

Communities and environments surrounding informal recycling have been found to have higher-than-background levels of heavy metals in soil, water, air and agricultural products [18]-[20]. In informal settings, recycling activities often take place in or near homes or in community areas, exposing recyclers and their families to harmful substances. Workers in the informal sector frequently lack labor rights and occupational health regulations, making them more vulnerable to precarious workplace conditions [11]. In addition to workers, children are especially susceptible to health effects caused or exacerbated by exposure to heavy metals in e-waste recycling areas [17], [21]. The tendency of informal workers to be from marginalized and lower socioeconomic status segments of the population further compound the justice issues surrounding e-waste.

The global trade of e-waste saddles developing countries with a disproportionate burden of the environmental health impacts of recycling. Additionally, the domestic flow of e-waste in these countries is growing as the consumer base for new and used electronic goods grows. High volumes of e-waste and low capacity to regulate, contain, and properly handle hazardous materials interact to form a potential environmental health crisis for current and future generations.

1.2 Dissertation background

This dissertation encompasses work that is part of a collaborative project between researchers at the University of Michigan and partners in Chile and Thailand. Researchers, students, health professionals, community volunteers, local government officials, and local healthcare institutions were involved in the design and implementation of research projects in each country. The decision to conduct research in Thailand and Chile stemmed from an observation that many of the environmental health studies published on e-waste recycling focus on a handful of countries, including China, India, and Ghana [22]. As e-waste recycling is still an emerging economy, geographic variances in product types, recycling methods, policies, and other characteristics are likely to have an influence on environmental health impacts. Using two geographically, socially, ethnically, and politically distinct populations allowed us to better contextualize our results.

The objective of the overall project was to employ a semi-community-based approach to investigate major questions regarding health issues related to e-waste with a multidisciplinary team of experts bringing together ideas from the fields of policy and ethnography, engineering, and public health. The focus of this dissertation was on the environmental health aspects of informal e-waste recycling in both countries; however, the research has been enriched by the interplay between experts in different fields and stakeholders involved in the research design and data collection processes. Figure 1-1 shows the location of the study sites in each country.

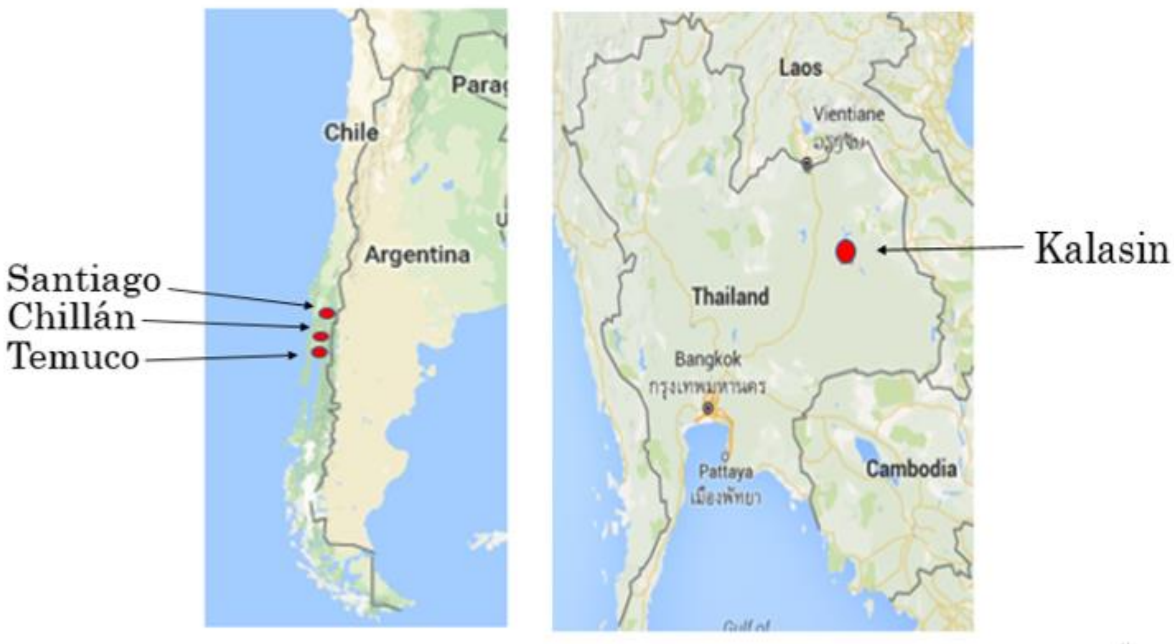


Figure 1-1 Location of study sites in Chile and in Thailand.

The study site in Thailand is a traditionally agricultural community in the Northeastern region of the country where a large portion of the population has adopted e-waste recycling as a supplementary source of income. Workers often perform e-waste recycling activities between rice harvests alongside family in their home, or in the home of a community member for whom they work as a minimum wage employee. Outside of agriculture and e-waste recycling, there are few other employment opportunities in or near the community, and therefore e-waste has become a very important, and transformative, source of income.

Three study sites were used in Chile: Chillan, Temuco, and Santiago. Although Chile is classified by the World Bank as a high-income country, there is significant economic inequality between rich and poor. The participants in this study were from lower-income neighborhoods in each of the three sites. Similar to Thailand, e-waste recycling provides a valuable employment opportunity to lower-income populations, and additionally provides a benefit to the surrounding communities by sorting and collecting recyclables from waste streams.

1.3 Motivation for research

Global awareness of the growing e-waste problem has not escaped the attention of researchers. Figure 1-2 shows the number of publications, by year, under the topic search term “e-waste” on Web of Science [23]. Since the early 2000’s, the number of publications focused on e-waste has increased exponentially, and these publications span numerous fields, including policy, engineering, natural resources, and public health. This dissertation investigated three pressing and diverse questions under the umbrella of total worker health (TWH). TWH, an initiative created by the US National Institute for Occupational Safety and Health, is the integration of traditional occupational health and safety objectives with those that promote the overall well-being of workers through the concept that work is a social determinant of health [24]. This framework allows for a bridge between health promotion and occupational health practices [25]. Given the community exposures likely to occur with informal e-waste recycling, this dissertation addressed these to better understand non-occupational exposure, as well as differentiate between what a worker is exposed to during working hours and what additional exposures occur during non-working hours. Despite the growing body of research in e-waste and environmental health, important questions remain on how workers and communities are impacted by e-waste recycling activities.

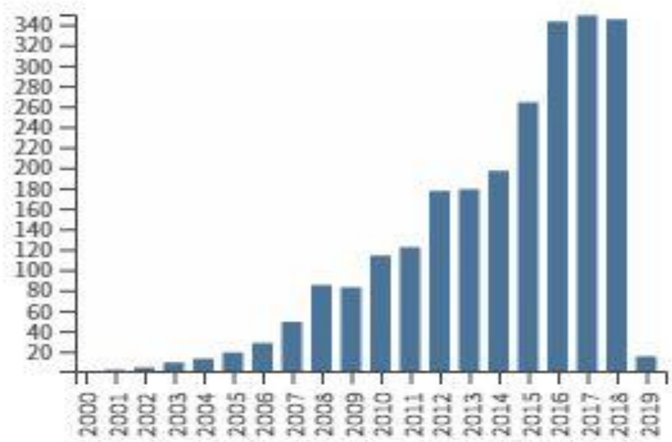


Figure 1-2 Results from Web of Science search for "e-waste" showing the number of publications under the topic search term "e-waste" by year through December 2018.

Exposures to metals from e-waste recycling is of particular concern to human health given their relative abundance in electronic products and environmental persistence. Workers and community members have been shown to be exposed to e-waste-related metals through several routes: inhalation of e-waste particulate matter during burning and manual disassembly, ingestion of particles generated by manual disassembly, dermal exposure and absorption to metal particles, and ingestion of plants and/o r animals that have taken up metals that have entered the environment [20], [26]-[31]. Several studies of metal concentrations in human biomarker samples have indicated elevated levels of metals, particularly lead [32]-[36]. Several studies have shown that metal biomarker concentrations in occupationally exposed groups are generally higher than non-occupationally exposed groups; however, this trend varies depending on the specific metal and population [34], [37]-[39]. The heterogeneity of e-waste materials, recycling methods, and the presence – or lack – of occupational controls, all contribute to the differences in study observations. It is not known what the largest contributing routes of exposure are for different metals, nor what the differences in levels of exposure are for occupational versus non-occupational populations. These lines are further blurred in informal settings where recycling occurs inside of the home, where workers are then doubly-exposed during work and non-work hours. Furthermore, in terms of monitoring exposures to metals from e-waste, there is no evidence for the optimum sample type to best represent exposure risk. It is not possible to measure the “true,” long-term exposure to metals; the methods available all provide varying degrees of approximation and estimation of this unmeasurable exposure [40].   Although studies have measured a variety of sample types, including biomarkers, surface wipe samples, air samples, and environmental samples, it is unclear which type of sample best measures the true exposure to metals from e-waste [20], [35], [39], [401]-[43].

Beyond chemical exposure, e-waste workers in the informal sector encounter an array of workplace hazards that have potential to cause injury [13], [44]. Because they are not part of a formal, regulated industrial or commercial sector, these injuries are not reported to any regulatory or surveillance programs and therefore the frequency, causes, and types of injuries are not known. Accurate assessments of injury risk during informal e-waste recycling are important for the development of workplace interventions. What may otherwise be considered a small injury is of more concern is e-waste populations who are more likely to have limited access to health care in the event of an injury [45]. A qualitative study on the working conditions of e-waste recyclers in Agbogbloshie, Ghana found that most workers were working in substandard conditions. Workplace sanitation, lack of training, absence of any personal protective equipment (PPE), poor wages, and long working hours were all cited as realities of the working conditions [46]. A study of 279 e-waste workers in Nigeria reported that 68% were injured during work in the previous 6 months, and 89% were injured at some point during their time working in recycling [47]. However, the external validity of these studies is unknown, and more information is needed to determine the risk of injury in e-waste recycling. Additionally, injury risk is likely to vary by job and task within e-waste recycling, and so again more information is needed to accurately describe workplace injury risks in order to develop results that can be translated into interventions to protect worker health.

The potential hazards from informal e-waste recycling are rather apparent, given the litany of hazardous chemicals and precarious workplace conditions. Perhaps less apparent are the benefits, and opportunities for improvement. With the valuable materials contained in e-waste, recycling has the potential to be a lucrative industry. Formal recycling, however, has large overhead costs [48]. The informal sector has smaller individual overhead costs by comparison, sector and provides flexible and potentially lucrative individual employment opportunities [49]. Several studies have calculated the economic profit in the formal industry, but there is a dearth of information about informal industry profits [5]. Similarly, the flow of electronic products and materials in formal systems has been well-captured, particularly in some European countries, while there is a relative lack of information on the flow in informal systems [5], [50]-[52]. The true environmental health impacts from informal recycling cannot be estimated without understanding how much e-waste is being processed on smaller, local scales [53]. Informal recycling has been shown to be more efficient than formal recycling, both in the recovery of products from the waste stream and in the extraction of materials from products [54], [55]. Because informal e-waste recycling typically involves manual disassembly of products, the carbon emissions from electricity use can be expected to be low. A study comparing the benefits of a formal recycling system with an incineration scenario in Switzerland found that recycling e-waste has a net positive environmental effect [50]. It is unknown if this positive environmental effect carries over to the informal sector considering the lack of environmental controls. In addition, the Swiss study calculated the impact for a mixture of electronic products. This dissertation evaluated the impact per individual product for four selected e-waste products, providing information on what types of e-waste have larger environmental impacts.

1.4 Research Overview

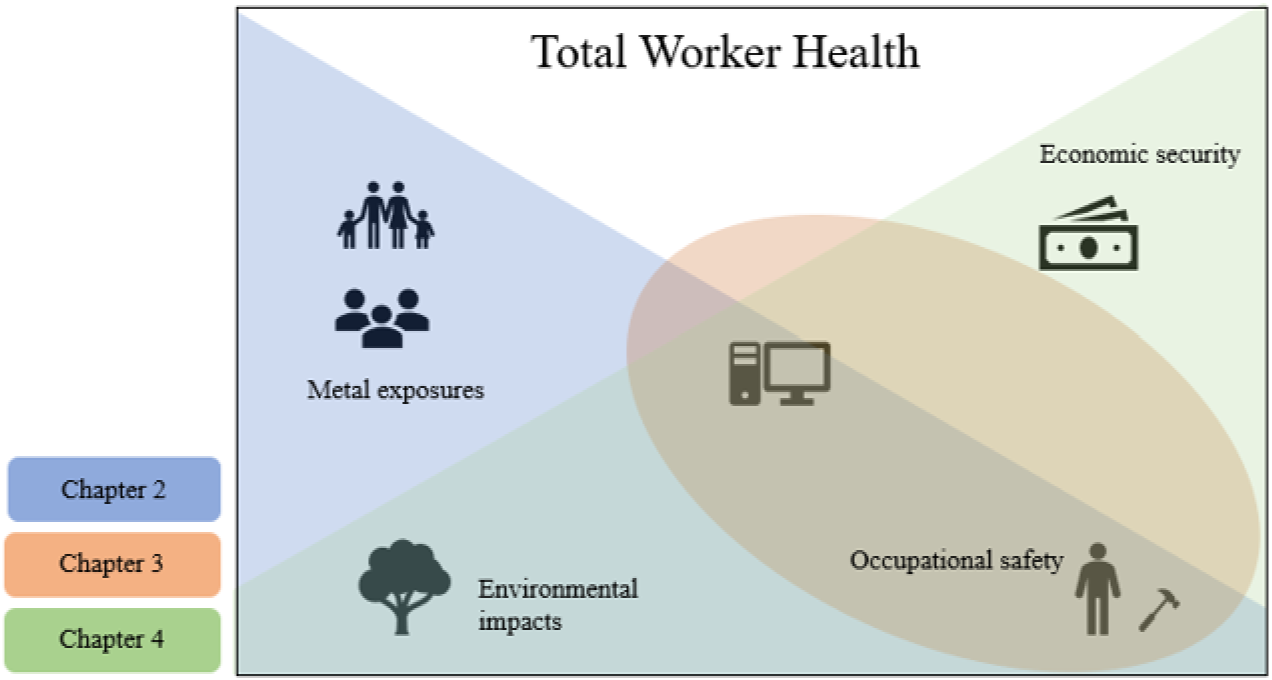


Figure 1-3 Diagram showing the relationship of the three dissertation chapters and the relationships between one another.

The purpose of this dissertation was to explore the environmental health impacts of e-waste recycling. Figure 1-3 shows the relationship between each chapter, and how all concepts are united under the concept of TWH. The chapters provide an exploration of chemical and physical hazards associated with e-waste as well as environmental and economic impacts and how they interact. The results allow for an in-depth understanding of the major areas of concern in informal e-waste recycling, and what potential interventions might be made that simultaneously protect the environment, the community, workers, and preserve the economic well-being of those dependent on the industry. The chapters of this dissertation are structured as follows:

Chapter 2 evaluated the association between environmental exposures and internal biomarkers with a focus on Thailand and Chile. The primary objectives of this study were: to investigate which potential routes of exposures to metals are of greatest concern to humans and assess the relative levels of exposures between workers and non-workers; to determine the best sample type when selecting for a marker of exposure to a given metal; and to compare the blood and urine biomarkers measured in the population.

Chapter 3 quantified the prevalence and risk of injury among e-waste workers with a focus on Thailand and Chile using a combination of survey data and risk factor information extracted from video footage. The primary objectives of this chapter were to determine which aspects of e-waste recycling in the informal sector present the greatest rates, and risks, of injury. We also examined exposures to noise during e-waste recycling and evaluated hearing outcomes.

Chapter 4 utilized a material flow analysis (MFA) and life cycle assessment (LCA) to determine the economic and environmental benefit of e-waste recycling, with a focus on Thailand. The primary objectives of this chapter were: to quantify the flow of four select e-waste products into and out of a neighborhood in northeastern Thailand; to determine the economic benefit generated by this flow; and to determine the net environmental cost or benefit of recycling each of the four products by informal methods compared to a baseline scenario of disposal in a landfill.

Chapter 5 integrates the findings from the previous three chapters and highlights significant findings and identifying future areas for research. The chapter includes recommendations for e-waste workers, public health practitioners, electronic recycling systems, and other researchers. This chapter also provides a final note on the importance of the considerations of the environmental justice issues surrounding e-waste.

1.5 Bibliography

1. Tansel, B. From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35–45 (2009).

2. Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M. & Böni, H. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25, 436–458 (2005).

3. Baldé, C. P., Forti, V., Kuehr, R. & Stegmann, P. The global e-waste monitor - 2017. (2017).

4. Cui, J. & Forssberg, E. Characterization of shredded television scrap and implications for materials recovery. Waste Manag. 27, 415–424 (2007).

5. Cucchiella, F., Adamo, I. D., Koh, S. C. L. & Rosa, P. Recycling of WEEEs : An economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev. 51, 263–272 (2015).

6. Robinson, B. H. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–91 (2009).

7. Mueller, S. R., Wäger, P. A., Widmer, R. & Williams, I. D. A geological reconnaissance of electrical and electronic waste as a source for rare earth metals. Waste Manag. 45, 226–234 (2015).

8. Zeng, X., Mathews, J. A. & Li, J. Urban mining of E-waste is becoming more cost-effective than virgin mining. Environmental Sci. Technol. 52, 4835–4841 (2018).

9. United Nations Environment Programme. Basel Convention on the control of transboundary movements of hazardous wastes protocol on liability and compensation. 120 (2014).

10. Balde, C. P., Forti, V., Gray, V., Kuehr, R. & Stegmann, P. The Global E-waste Monitor 2017. The Global E-waste Monitor (2017).

11. Lundgren, K. The global impact of e-waste: Addressing the challenge. International Labour Office (2012).

12. Wang, F. et al. The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag. 32, 2134–2146 (2012).

13. Perkins, D. N., Brune Drisse, M.-N., Nxele, T. & Sly, P. D. E-waste: a global hazard. Ann. Glob. Heal. 80, 286–95 (2014).

14. Zheng, J. et al. Disruption of thyroid hormone (TH) levels and TH-regulated gene expression by polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and hydroxylated PCBs in e-waste recycling workers. Environ. Int. (2017). doi:10.1016/j.envint.2017.02.009

15. Wong, M. H. et al. Export of toxic chemicals - a review of the case of uncontrolled electronic-waste recycling. Environ. Pollut. 149, 131–40 (2007).

16. Sthiannopkao, S. & Wong, M. H. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Sci. Total Environ. 463–464, 1147–1153 (2013).

17. Heacock, M. et al. E-Waste and Harm to Vulnerable Populations: A Growing Global Problem. Environ. Health Perspect. 550, 550–555 (2015).

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

19. Wu, Q. et al. Heavy metal contamination of soil and water in the vicinity of an abandoned e-waste recycling site: Implications for dissemination of heavy metals. Sci. Total Environ. 506–507, 217–225 (2015).

20. Zheng, J. et al. Heavy metals in food, house dust, and water from an e-waste recycling area in South China and the potential risk to human health. Ecotoxicol. Environ. Saf. 96, 205–212 (2013).

21. Zeng, X., Xu, X., Boezen, H. M. & Huo, X. Children with health impairments by heavy metals in an e-waste recycling area. Chemosphere 148, 408–15 (2016).

22. Iqbal, M. et al. Emerging issue of e-waste in Pakistan: A review of status, research needs and data gaps. Environ. Pollut. 207, 308–318 (2015).

23. Web of Science. Citation report for 'e-waste' search Available at: https://wcs-webofknowledge-com.proxy.lib.umich.edu/RA/analyze.do?product=WOS&SID=5C9mQOrTvnbRCkeZLt5&field=TASCA_JCRCategories_JCRCategories_en&yearSort=false. (Accessed: 16th December 2018)

24. Centers fo Disease Control and Prevention (CDC) & National Institute for Occupational Health and Safety (NIOSH). What is Total Worker Health. Available at: https://www.cdc.gov/niosh/twh/totalhealth.html. (Accessed: 30th October 2018)

25. Schill, A. L. & Chosewood, L. C. The NIOSH Total Worker HealthTM program: an overview. J. Occup. Environ. Med. 55, S8-11 (2013).

26. 26. Zhao, G. F., Zhou, H. D. & Wang, Z. J. Concentrations of selected heavy metals in food from four e-waste disassembly localities and daily intake by local residents. J. Environ. Sci. Heal. Part A Toxic/Hazardous Subst. Environ. Eng. 45, 824–835 (2010).

27. Yekeen, T. A. et al. Assessment of health risk of trace metal pollution in surface soil and road dust from e-waste recycling area in China. Environ. Sci. Pollut. Res. 23, 17511–17524 (2016).

28. Wu, Y. et al. Tetrabromobisphenol A and heavy metal exposure via dust ingestion in an e-waste recycling region in Southeast China. Sci. Total Environ. 541, 356–364 (2016).

29. Simmons, R. W., Pongsakul, P., Saiyasitpanich, D. & Klinphoklap, S. Elevated levels of ladmium and zinc in paddy soils and elevated levels of cadmium in rice grain downstream of a zinc mineralized area in Thailand: Implications for public health. Environ. Geochem. Health 27, 501–511 (2005).

30. Lau, W. K. Y., Liang, P., Man, Y. B., Chung, S. S. & Wong, M. H. Human health risk assessment based on trace metals in suspended air particulates, surface dust, and floor dust from e-waste recycling workshops in Hong Kong, China. Environ. Sci. Pollut. Res. Int. 21, 3813–25 (2014).

31. ATSDR. Toxic Guide for Lead. (2007).

32. Noguchi, T. et al. Exposure assessment of lead to workers and children in the battery recycling craft village, Dong Mai, Vietnam. J. Mater. Cycles Waste Manag. 16, 46–51 (2014).

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

34. Julander, A. et al. Formal recycling of e-waste leads to increased exposure to toxic metals: an occupational exposure study from Sweden. Environ. Int. 73, 243–51 (2014).

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

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

37. Wang, T. et al. Use of scalp hair as indicator of human exposure to heavy metals in an electronic waste recycling area. Environ. Pollut. 157, 2445–2451 (2009).

38. Schecter, A. et al. Biomonitoring of metals, polybrominated diphenyl ethers, polychlorinated biphenyls, persistent pesticides in Vietnamese female electronic waste recyclers. J. Occup. Environ. Med. 60, (2017).

39. Ni, W. et al. Hair mercury concentrations and associated factors in an electronic waste recycling area, Guiyu, China. Environ. Res. 128, 84–91 (2014).

40. White, E. Design and interpretation of studies of differential exposure measurement error. Am. J. Epidemiol. 157, 380–387 (2003).

41. Wang, F., Zhao, Y., Zhang, T., Duan, C. & Wang, L. Mineralogical analysis of dust collected from typical recycling line of waste printed circuit boards. Waste Manag. 43, 434–441 (2015).

42. Lau, W. K. Y., Liange, P., Man, Y. B., Chung, S. S. & Wong, M. H. Human health risk assessment based on trace metals in suspended air particulates, surface dust, and floor dust from e-waste recycling workshops in Hong Kong, China. Environ. Sci. Pollut. Res. 21, 3813–3825 (2014).

43. Huo, X. et al. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ. Health Perspect. 115, 1113–1117 (2007).

44. Pinto, V. N. E-waste hazard: The impending challenge. Indian J. Occup. Environ. Med. 12, 65–70 (2008).

45. Asampong, E. et al. Health seeking behaviours among electronic waste workers in Ghana. BMC Public Health 15, 1065 (2015).

46. Akormedi, M., Asampong, E. & Fobil, J. N. Working conditions and environmental exposures among electronic waste workers in Ghana. Int. J. Occup. Environ. Health 19, 278–286 (2013).

47. Ohajinwa, C. M. et al. Prevalence and injury patterns among electronic waste workers in the informal sector in Nigeria. Inj. Prev. 24, 185–192 (2018).

48. Schmidt, C. W. Unfair trade: e-waste in Africa. Environ. Heal. Perspect. 114, 232–235 (2006).

49. Chi, X., Streicher-Porte, M., Wang, M. Y. L. & Reuter, M. A. Informal electronic waste recycling: A sector review with special focus on China. Waste Manag. 31, 731–742 (2011).

50. Hischier, R., Wäger, P. & Gauglhofer, J. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ. Impact Assess. Rev. 25, 525–539 (2005).

51. Stenvall, E., Tostar, S., Boldizar, A., Foreman, M. R. S. J. & Möller, K. An analysis of the composition and metal contamination of plastics from waste electrical and electronic equipment (WEEE). Waste Manag. 33, 915–922 (2013).

52. Balde, C. P. et al. E-waste statistics: Guidelines on classifications, reporting and indicators. United Nations University IAS - SCYCLE (2015).

53. Davis, J. M., Akese, G. & Garb, Y. Beyond the pollution haven hypothesis: Where and why do e-waste hubs emerge and what does this mean for policies and interventions? Geoforum 1–10 (2018). doi:10.1016/j.geoforum.2018.09.020

54. Scheinberg et. al. The Economics of the Informal Sector in Solid Waste Management: Economic Aspects of the Informal Sector in Solid Waste Management. GTZ and CWG, Eschborn, Germany. (2010).

55. Davis, J. M. & Garb, Y. A model for partnering with the informal e-waste industry: Rationale, principles and a case study. Resour. Conserv. Recycl. 105, 73–83 (2015).

Chapter 2 : Evaluation of Routes of Exposures to Metals Among Electronic Waste Workers and Community Members in Thailand and Chile

Chapter 2 Abstract

Background: Informal e-waste recycling in Thailand and Chile potentially exposes workers and community members to metals through several routes. Recycling activities can contaminate the local environment and presents workers and community members alike with non-occupational exposures. Workers are more exposed to e-waste activities, and therefore may have increased risk of metal exposures.

Objectives: This study had four objectives. First, to measure concentrations of metals in environmental media, including soil, water, rice, environmental air, personal and area air, and surface dust. Second, to compare occupational and non-occupational exposures in Thailand through examination of metal biomarkers in blood and urine, and to compare occupational exposures between Thailand and Chile. Third, to compare the environmental metal concentrations with those of human exposure groups to determine which routes of exposure are most relevant for occupationally- and non-occupationally exposed groups. Fourth, to use the Method of Triads to determine which exposure sample types have the highest validity coefficient to estimate the true exposure.

Methods: Samples of environmental media and biomarkers were collected in Thailand and Chile and then analyzed for metal concentrations. Summary statistics were run and comparisons using t-tests were made between the groups. Multiple linear regression models were run with demographic variables to measure the association of socio-economic and biological explanatory variables with metal concentrations. Finally, the method of triads was used to calculate validity coefficients.

Results: Elevated concentrations of metals were found in soil, rice, and surface water samples. The occupational exposure group in Thailand had overall higher concentrations of all metals in blood and urine except for Cadmium than both the Thai community exposure group and the Chilean occupational exposure group. The Thai community exposure group had higher biomarker concentrations of some metals than then Chilean occupational group, suggesting that environmental contamination presents an important route of exposure to metals from e-waste. The Method of Triads shows that wipe samples have the highest validity coefficient for a few metal types, but more studies are needed to increase confidence in this approach.

Conclusions: Hygiene practices are important in containing e-waste exposures to metals. Communities where informal e-waste recycling occurs are at increased risk of exposure to metals.

2.1 Introduction

2.1.1 Routes and Pathways of Exposure

Metals contained in electronics can be released to the environment during recycling activities such as storage, dismantling, and burning of electronics [1]-[3]. These activities result in elevated levels of metals at e-waste recycling sites, which then present a chance for human exposure [4]-[6]. Improper controls to limit or contain releases of metals into the environment place e-waste workers, as well as community members, at risk of direct or indirect exposures to e-waste [7]. These potential exposures raise public health concerns [8].

Once in the environment, humans can be exposed to metals through multiple routes and pathways. Some of the more direct pathways of exposure include ingestion or inhalation of dust resulting from dismantling activities or from atmospheric deposition of particles after burning e-waste [9], [10]. Surface dust at e-waste recycling facilities is known to contain metals and other toxicants [10]-[12]. In informal settings, e-waste may take place in or near homes, generating contaminated surface dust throughout the home. This represents an important exposure pathway, as surface dust can be easily ingested by adults and children alike. Metals can also be inhaled in the form of smoke during e-waste burning, or during dismantling when particles are aerosolized. Studies in formal recycling settings have found that workers are exposed to airborne lead (Pb), cadmium (Cd), and nickel (Ni) [13], [14]. Additionally, some metals, such as Ni and Pb, are known skin allergens and can even penetrate the skin, creating a dermal route of exposure under certain conditions, such as in the presence of sweat [15], [16].

Indirect pathways of exposure include ingestion or inhalation of contaminated environmental media. The informal sector lacks the physical and regulatory infrastructure required to minimize the spread of metal contamination to the environment [17]. Dismantling of e-waste can generate dust and metal scrap that enter the environment directly. Leaching during rain events and non-confined smoke plumes can also contaminate crops and the environment near e-waste recycling areas [18]. Once in the environment, metals may transform into biologically available forms and can disrupt ecosystems [19]. Additionally, metals such as Pb, Cd, and others found in e-waste are persistent pollutants and are difficult to remediate [20].

Metal particles, ash, and scrap pieces generated during e-waste disassembly can enter the environment directly through the soil. A study examining metal concentrations in a former e-waste burn site in China found elevated concentrations of Cd, Pb, copper (Cu), and zinc (Zn) [21]. Other studies have found elevated levels of metals in soils from agricultural fields, road dust, and soil near e-waste recycling areas [4], [10], [18], [22], [23]. During rain events, these metals can wash into rivers and streams where they contaminate sediments and affect aquatic ecosystems [24], [25].

The uptake of heavy metals by crops in areas where agriculture and e-waste occur in close proximity has been demonstrated in several studies, presenting an additional exposure pathway for workers and community members who consume these crops as a diet staple [21], [26]. Rice (*Oryza sativa*) has consistently been associated with heavy metal uptake near e-waste recycling operations around the globe [21], [27]-[29]. In particular, rice is known to uptake Cd and other metals from contaminated soils and incorporate the metals into the grains of the rice plant [30]. These metals then enter the food chain and are passed to humans once ingested.

Surface waters near e-waste sites have been found to have a high concentration of metals through runoff of contaminated surface soils [18]. A 2015 study of a former e-waste recycling site in China showed that groundwater had low levels of heavy metal contamination, while surface waters, often used for crop irrigation, were highly contaminated with Cd and Cu [31]. A different study found that groundwater near a large e-waste site had Pb concentrations higher than the acceptable range set by the US EPA, and that the exposure from ground water presented a greater risk than from inhalation or dermal contact with dust [28]. In summary, there is evidence in the literature indicating that unchecked e-waste recycling can pollute the environment with metals.

2.1.2 Biomarkers

In addition to environmental contamination, e-waste recycling presents a risk of human exposures to metals. Studies of e-waste workers in both the formal and informal sectors in other countries have shown higher levels of metals in blood and urine [13], [32]. Some metals found in e-waste, such as Cu, Zn, and iron (Fe), are essential elements that are only toxic at very high concentrations. Other metals, including Pb and Cd, are considered toxic even at very low doses [16], [33]. Workers in Agbogbloshie, Ghana were found to have elevated concentrations of blood Cd and Pb [34]. A second study conducted at the same e-waste site found elevated levels of urinary Fe, Sb, and Pb [35]. Other studies from e-waste sites worldwide have found varying concentrations of different metals in occupationally and non-occupationally-exposed populations [13], [36]-[40]. While a pattern of increased concentration of metals in biomarkers from human populations exposed to e-waste has been identified in the literature, the specific metals that are elevated vary from population to population, possibly due to the complex composition of the e-waste stream. Additionally, previous research has studied various aspects of environmental contamination from e-waste sites, but few studies have compared environmental contamination with biomarkers [41].

The choice of biomarkers, including element types and biological sample type, is of critical importance. Exposure concentration, duration, and chemical form of metal are all factors affecting personal metabolism, including absorption and excretion. Blood biomarkers can include whole blood, serum, and plasma. Whole blood contains all parts of blood, while serum is similar to plasma but excludes clotting factors [42]. Depending on the toxicant, plasma biomarkers sometimes show a more linear relationship between exposure and concentration changes than whole blood [43]. Blood biomarkers for some metals, like Cu, Mn, and Pb, are more suitable for long-term exposure than urinary biomarkers [43]-[45].

Urinary biomarkers are often used as an alternative to blood since urine collection is less invasive [46]. With most metals, we assume that absorption and excretion of the metal in urine is proportional. For some metals, including Cd, urinary concentrations are more an indication of long-term body burden that short-term exposures [44], [45]. Important considerations of urinary biomarkers include the time period during which the sample was collected (i.e., spot samples, 24-hour urine samples, first morning void, etc.), as the concentrations of metals in urine fluctuate throughout the day [47]. Urine concentrations are often adjusted for differences in hydration status through the use of creatinine concentration or specific gravity, and each method introduces its own potential sources of error [48].

2.1.3 Study objectives

This study had four core objectives. The first was to quantify the concentrations of metals in environmental media from an e-waste recycling community in Thailand. The second was to measure and compare the concentrations of metals in human blood and urine samples for e-waste workers in Thailand and in Chile, as well as to compare worker and non-worker concentrations within the Thai study site. Third, this study related the concentrations of metals found in environmental samples with those found in human biomarkers to form hypotheses about which routes and pathways of exposure may be the most relevant for occupationally- and non-occupationally exposed populations.

The fourth and final objective of this study was to employ the Method of Triads to evaluate which type of sample (surface wipe, air samples, blood/serum, or urine) is most accurate in measuring exposures to different metals from e-waste. This method has been used previously in epidemiological studies of nutritional intake [49]-[57], and, to a lesser degree, for environmental health hazards and health sciences [58]-[61]. The method of triads offers a means to evaluate the validity of three different estimates of exposure by assessing the interrelationships between these estimates [62]. The results of the method of triads are a valuable tool for selecting which among the many possible routes and pathways of exposure is the most valid for estimating the true, unknown dose [49], [63]. This type of sample selection is particularly relevant given the high expense of collecting and analyzing samples and can be employed by future researchers, policy makers, and public health practitioner to regulate and monitor environmental and human contamination from e-waste metals. A visual explanation of the method of triads is given in Figure 2-1, which is modified from Pereira et al, 2016 [49].

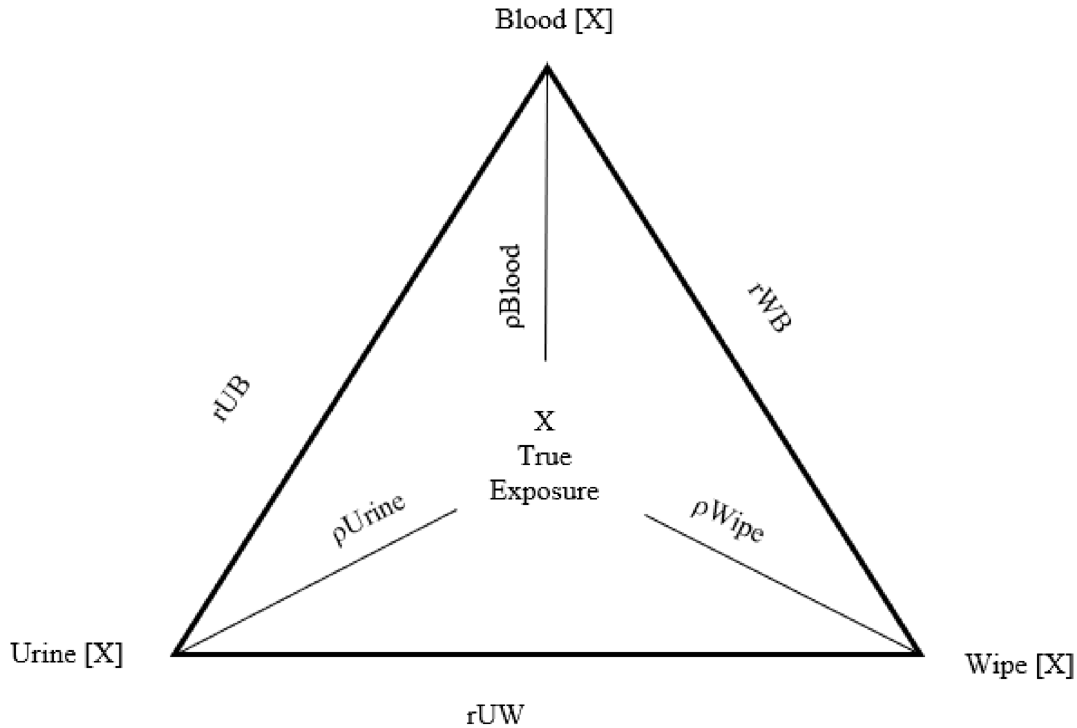


Figure 2-1 Conceptual diagram of the method of triads which is used to estimate the exposure based on correlations, r, between urine, wipe, and blood concentrations of a given metal, X. The validity coefficient, ρ, is the correlation between the measurement and the true, unknown exposure. Modified from Pereira et al, 2016.

2.2 Methods

2.2.1 Study site

This study was approved by the Institutional Review Board of the University of Michigan (HUM0014562) in the United States, Mae Fah Luang University (MFU) in Thailand (REH-59104), and the University of Chile – Santiago (Archive Project Nº 101-2017; Act Nº 45). Informed consent was obtained from all subjects prior to participation in any study procedures.

Data for this study were collected from Thailand and Chile. Three exposure groups were selected for this study:

- An occupationally-exposed group of e-waste workers in Thailand.
- An occupationally-exposed group of e-waste workers in Chile.
- A non-occupationally-exposed "community group" was recruited in Thailand from the same e-waste community. This community group, which did not perform e-waste recycling, was hypothesized to be exposed to e-waste metals not through job-related activities, but through various environmental media in the community or in their own/community member's homes where e-waste recycling occurs.

The study site in Thailand was a rural community in the northeastern part of the country. Historically agrarian, the community has incorporated e-waste recycling as a major source of income to supplement incomes still largely centered around rice farming. Recycling occurs in living spaces rather than in formal work areas, and is an activity often performed collectively among adult family members. The community contains an unlined refuse dump in the middle of community rice fields where some e-waste activities, primarily burning e-waste and breaking/disposing of leaded-glass, occurs. Data for this study were collected in Thailand between June 2016 and August 2017. Using convenience sampling, we recruited e-waste recyclers as well as community members. On the recommendation of local collaborators, random sampling was determined to be neither feasible nor appropriate due to local culture and custom.

Three communities in Chile participated in this study. The first was comprised of several neighborhoods within the urban capital city, Santiago, Chile. The second community, Chillan, and the third community, Temuco, were more rural and less densely populated than Santiago. E-waste workers were recruited during July and August of 2017 using convenience sampling methods. Informal recyclers are not listed on registries in Chile, and so random sampling techniques were not feasible.

2.2.2 Survey methods

Surveys were conducted through in-person interviews by a native language (Thai/Spanish) speaking member of the research team. Information was collected on occupational history, e-waste activities, and demographic variables (See Appendix A). In Thailand, data collected on income was compared with the Thai Ministry of Labor's minimum wage law of 6,100 Thai Baht per month (based on 305 Thai Baht per day and a 5-day work week), approximately equivalent to 190 USD [64]. In Chile, self-reported monthly income data was compared with the Chilean monthly minimum wage of 270,000 pesos, approximately 400 USD [64].

2.2.3 Environmental sample collection and analysis

Several types of environmental samples were collected. In both countries, surface wipe and area air samples were collected. In Thailand, samples of rice, soil, surface water, personal, and environmental air samples were collected in addition. Details on the methods used to collect and analyze each sample type are below.

2.2.3.1 Rice and soil

Locally-grown rice samples were purchased from various parts of the research site in Thailand. A one-kg sample of rice was weighed and collected in Ziploc bags. No rice or other agricultural samples were collected from Chile as the study sites were primarily urban areas.

Soil samples were collected from various parts of the community, including in yards of homes and in communal areas using EPA soil collection procedures [65]. One-kg samples were mixed using quartering method, debris removed, and stored in a Ziploc bag.

Rice and soil samples were stored in a cool, dry location prior to analysis. Samples were analyzed for concentration of 8 heavy metals associated with electronic waste recycling: Cd, Cu, Fe, Mn, Ni, Pb, and Zn. These metals were selected based on their prevalence in electronic products [66], [67]. The International Organization for Standardization (ISO)-certified Thailand Central Laboratory used microwave-assisted acid digestion followed by Atomic Absorption Spectrophotometry to analyze rice and soil samples [68].

For comparison purposes, three recommended reference levels were used to evaluate metal concentrations in rice, as no one reference type was available for all seven metals. The Maximum Level (ML) is set by the Joint Food and Agriculture Organization of the United Nations/World Health Organization (Joint FAO/WHO) as the maximum concentration of a substance permitted in a commodity for human consumption [69]-[71]. The Provisional Maximum Tolerable Daily Intake (PMTDI) is also set by the Joint FAO/WHO, and is the maximum amount of a contaminant that can be ingested per day by body weight; this recommendation accounts for toxicants that accumulate within the body [72], [73]. The Tolerable Upper Intake Limit (TUIL), set by the Food and Nutrition Board at the Institute of Medicine, National Academies of the United States, is the maximum daily amount of a chemical that can be ingested where no health effects are expected for most individuals [74]. Rice sample concentrations from Thailand were calculated to be comparable to the associated reference type. For TUIL and PMTDI, the dietary intake was calculated for rice samples using a 60 kg body weight and 0.28 kg rice consumed daily, based on values taken from a study on a northeastern Thailand population [75].

2.2.3.2 Surface water

Water samples were collected from two areas: ≤1 and > 1 km of the community refuse dump. Samples were collected according to EPA surface water sampling protocol SESDPROC-201-R3 [76]. Samples were collected in high-density polyethylene bottles and stored at 4°C prior to analysis. Water samples were analyzed at the Thailand Central Laboratory using ICP-MS [77]. Samples were tested for Cd, Cu, and Pb as these elements are found in electronics, are known to impact human health (Cu toxicity occurs at levels beyond those needed for biological functioning), and because of the existence of regulatory limits for Cu and Pb in drinking water to which our results could be compared [66], [67], [78].

2.2.3.3 Wipe and air samples

Wipe samples were collected in Thailand and in Chile using OSHA surface wipe sampling protocols [79]. A 10 cm x 10 cm template was used to collect surface dust from areas where food was prepared or consumed, as well as on work benches. Samples were stored in 100-mL plastic centrifuge tubes and sealed with parafilm for storage.

Three types of air samples were collected. Area samples were collected in Thailand and Chile by mounting the pump and cassette on or adjacent to the subject’s work station. Environmental samples were collected in Thailand by affixing the pump and cassette to a tripod and placing the tripod in a communal area, such as a community temple. Environmental air samples were not collected during rain events. Finally, personal breathing zones (PBZ) samples were collected in Thailand by attaching the pump to the subject and placing the filter cassette in the sampled individual’s breathing zone.

All air samples were collected using SKC Airchek-52 Personal Air Sampling Pumps. Pumps were calibrated before and after sampling events using a DryCal to check flow rate. The average of the pre- and post-sampling flow rates was used to later calculate the volume of air sampled. Samples were collected on 37-mm cassette filters with 0.8 μm cellulose ester membranes. The target air sampling time was 8-10 hours, or one work shift; however, subject activities, such as short working hours, occasionally limited sampling time. After collection, cassettes were sealed with parafilm and stored into a Ziplock bag.

Wipe and air samples were stored in cool, dry conditions until analysis at Bureau Veritas Laboratory in Novi, Michigan using OSHA method 125G for Inductively Coupled Plasma (ICP) analysis [80]. Wipe and air samples were analyzed for 13 metals associated with e-waste recycling: antimony (Sb), Beryllium (Be), Cd, chromium (Cr), cobalt (Co), Cu, Fe, Pb, Mn, molybdenum (Mo), Ni, vanadium (V), and Zn. These metals were selected because they are known to be included in electronic products, and thus might be present in air and wipe samples of e-waste recycling areas [67], [81]. One field blank was collected and analyzed for each day of sampling for both wipe and air samples. All samples were blank-corrected.

2.2.4 Blood and serum biomarker collection and analysis

Blood, serum, and urine samples were collected for analysis of eight metals: Aluminum (Al), Cd, Fe, Pb, Mn, Ni, Cu, and Zn. These metals were selected based on their prevalence in electronic products [66], [67]. Antecubital blood samples were collected from participants in a 4 mL heparin through assistance from certified nurses in Thailand and Chile. Serum samples were centrifuged immediately after collection. Freshly voided urine samples were collected in 50 mL acid-washed propylene sampling containers. Immediately after collection, a transfer pipette was used to place the urine into two 15-mL Corning Tubes. All samples were stored with parafilm to prevent leakage.

Blood samples for heavy metal analysis were stored at -20°C prior to analysis. Al, Fe, Mn, and Ni in whole blood and Cu and Zn in serum were measured using an Agilent 7500 ce Inductively Coupled Plasma-Mass Spectrometer (ICP-MS). Pb and Cd were measured in whole blood samples with Graphite Furnace-Atomic Absorption Spectroscopy (GF-AAS) using an Agilent 280Z AA spectrometer and a SpectrAA 880 Varain Spectrometer, respectively, using previously described methods [82]. For all blood analytes, blanks were measured at a rate of 5% of the total number of samples. All samples were blank-adjusted. The blood results for metal concentrations will be reported in µg/L, except for Pb which is reported as µg/dL.

2.2.5 Urine biomarker collection and analysis

Urine samples were stored in Vacutainer Plus Urinalysis tubes in a freezer at 4 °C. Samples were then frozen and transferred to the Thai Ministry of Public Health Central Laboratory in Bangkok for analysis. Concentrations of Al, Cu, Fe, Pb, Mn, and Zn, were measured with an Agilent 7500ce inductively coupled plasma mass spectrometer (ICP-MS) using previously described methods [83]. Samples were diluted by a factor of 10 using a 2% HNO 3 solution. Urinary Cd, Ni concentrations were determined via GF-AAS with a Agilent 280Z AA spectrometer using methods detailed previously [82]. Samples were diluted by a factor of 10 using a solution of 0.1% Triton X -100, 0.2% $(NH4)_2HPO_4$. Two types of reference materials were used to ensure instrument and procedure performance. Blanks were used as a quality control measure at a rate of 10% of the total number of urine samples. All samples were blank-adjusted. Urine samples were creatinine-adjusted to account for individual metabolism and hydration differences. The concentrations of urinary biomarkers will be reported as µg of analyte per g creatinine (µg/g).

2.2.6 Data cleaning and summary statistics

Non-detectable samples were assigned a value equal to the limit of detection (LOD) divided by $\sqrt{2}$ [84]. Left-censored distributions with more than 80% of the samples below the relevant limit of detection were not assigned new values, and data are presented as the maximum value and percent larger than the limit of detection rather than measures of central tendency and variance. Biomarkers with a high percentage of negative concentration results after blank-adjustment were dropped from the dataset. The normality of distributions was assessed visually using histograms. Data with skewed distributions were log-transformed. A value of 1.0 was added to analytes with concentrations smaller than 1 unit prior to log-transformation of that data series. Outliers were examined by plotting the data. Outliers were not removed unless the inclusion of the outlier created a significant association that was absent if the outlier were to be removed.

All statistical tests were performed using SPSS v.25 (IBM, Armonk, New York) and Stata v.15 (StataCorp, LLC, College Station, TX). Independent samples t-test (assuming unequal variance) were performed on continuous variables, while χ^2 tests were performed on categorical variables. Results were considered significant where $p < 0.05$. Tests of significance using two-sample t-tests were run between either the Thailand community group and the Thailand occupational group, or the two occupational groups (Thailand and Chile). No t-tests were run to compare the Thailand community exposure group and the Chile occupational exposure group because the objectives of the study were to compare occupational and community exposures (Thailand groups) and occupational groups in different settings (occupational groups).

2.2.7 Multiple linear regression

A multiple linear regression was conducted using several of the demographic variables to evaluate the association between demographic and work variables and concentrations of metals in blood and urine. All demographic predictor variables for all three exposure groups were checked for collinearity using variance inflation factors. Regressions were run separately for each exposure group using a robust estimator of variance.

2.2.8 Method of Triads

The Method of Triads can be used to estimate the validity coefficient of three methods of measuring a given exposure (in this case, metals exposure). This study evaluated which type of sample was the most valid measure of the "true" exposure to a given metal for each of the three study exposure groups (Thailand occupational exposure group, Thailand community exposure group, and Chile occupational exposure group). It should be noted that the term "validity" is the term used by the method, but does not mathematically represent the most valid measure. Rather, it represents the measure that is most correlated with the other two measures. The true internal exposure cannot be directly measured, as even biomarkers contain error introduced by laboratory analysis, temporal misalignment with environmental exposures and health outcomes of interest, and within-subject variation in concentrations and measurement errors [85], and can instead only be estimated (see Figure 2-1).

The Method of Triads was used to examine air samples (personal or area), wipe samples (work or food), and biomarkers (serum or urine). To be valid for use in the Method of Triads, correlation coefficients between variables must have a positive, and the measured exposures should be linearly associated linear associated with the underlying (unknown) "true" exposure

[76]. Additionally, the errors for each measure must be uncorrelated. The estimated validity coefficient represents the correlation between the unknown "true" internal exposure and the measured exposures to the metals of interest. All viable combinations were tested. Equation 1 below shows a sample calculation for the method of triads. The validity coefficients resulting from the method of triads should lie between 0 and 1, with coefficients closer to 1 representing a better measure of the true exposure.

$$VC_{BTX} = \sqrt{\left(\frac{r_{BU} * r_{BW}}{r_{UW}}\right)} \qquad VC_{UTX} = \sqrt{\left(\frac{r_{UB} * r_{UW}}{r_{BW}}\right)} \qquad VC_{WTX} = \sqrt{\left(\frac{r_{BW} * r_{UW}}{r_{BU}}\right)} \qquad (1)$$

Where:

VC = Validity coefficient;

r = correlation corrected for within-subject variation;

T is the true (unknown) value;

B = Blood concentration of metal X;

U= Urine concentration of metal X;

W=Wipe concentration of metal X.

2.3 Results

2.3.1 Environmental media measurements

2.3.1.1 Soil

Ten soil samples were collected from the study site in Thailand (Table 2-1). All ten soil samples had concentrations over the limit of detection for the seven metal analytes. The Dutch Target Value and Thailand non-e-waste levels are provided as reference values, and the results from soil concentrations of metals in other e-waste sites in Ghana and China are provided as comparisons [10], [86]-[88]. The mean Pb concentration was 104.5 mg/kg, which is 1.25 times higher than the Dutch Target Value and 6 times higher than the results from the non-e-waste study in Thailand [86], [87]. The mean soil Pb concentrations was below that found in studies from e-waste sites in Ghana, but slightly above the mean measured in China (3257, 213.6 mg/kg, respectively) [10], [88]. The mean Cd concentration of 1.69 mg/kg was more than double the Dutch Target value and 56 times higher than the non-e-waste site in Thailand. The mean Cd concentration in soil from this study was higher than that reported in the study from China, but lower than the mean reported in Ghana. Cu (306.1) and Zn (366.0) had mean concentrations near the Dutch Target Value (36 and 14.1 mg/kg, respectively) and the study from a non-e-waste site in Thailand (14.1, 23.9 mg/kg, respectively). The results from the Accra, Ghana study reported a mean Cu concentration nearly 4 times higher than our study (1190 mg/kg), but lower mean Zn (274 mg/kg). Overall, the soil samples in this study showed metal concentrations that were higher than the control values, and in some cases comparable or worse than concentrations found in other studies of major e-waste sites in other areas of the globe.

Table 2-1 Concentration of seven metals in soil (n=10) from Kalasin, Thailand with comparison values.

Site	**Kalasin, Thailand (this study)**	**Dutch Target Value [86]**	**Thailand (non-e-waste) [87]**	**Accra, Ghana [88]**	**Guiyu, China [10]**
Sample size (N)	10	N/A	318	70	44
			Mean (sd) (mg/kg)		
Cd	1.69 (3.5)	0.8	0.03	4.58 (0.5)	0.3
Cu	306.1 (681.5)	36	14.1	1190 (174)	-
Fe	11989 (13155.0)	-	-	-	-
Mn	1174 (3243.0)	-	-	-	606.6
Ni	13.96 (22.1)	35	13.5	-	-
Pb	104.5 (283.3)	85	17.5	3257 (254)	213.6
Zn	366.0 (972.2)	140	23.9	274 (14.5)	-

2.3.1.2 Water

Results for Cd, Cu, and Pb concentrations in water samples from Thailand are displayed in Table 2-2. Cd concentrations are compared with the US EPA's Aquatic Life Ambient Water

Quality Criteria (AWQC), 0.02 mg/L. None of the community samples (>1 km from refuse dump where e-waste burning and some disassembly occurs) had concentrations of Cd over the LOD, while 57.1% of the refuse dump samples (<1 km from refuse dump) were above the LOD. All water samples had Cu concentrations greater than the LOD. The mean and max values of the refuse dump samples were higher than those of the community samples. All but one sample had values of Pb above the LOD, and again the concentrations of the refuse dump samples were higher on average than those of the community samples.

Table 2-2 Concentration of three metals in environmental surface water from Kalasin, Thailand.

	Ref	**Refuse dump (n=14)**			**Community (n=7)**		
Metal	**(mg/L)**	**N(%) > LOD**	**Mean (SD) (mg/L)**	**Max (mg/L)**	**N(%) > LOD**	**Mean (SD) (mg/L)**	**Max (mg/L)**
Cd[1]	0.002	8 (57.1)	0.04 (0.1)	0.4	0	-	-
Cu[2]	1.30	14 (100)	0.9 (1.5)	5.8	7 (100)	0.02 (0.02)	0.1
Pb[2]	0.02	13 (92.9)	0.3 (0.8)	3.0	7 (100)	0.01 (0.02)	0.1

[1]US EPA Aquatic Life Ambient Water Quality Criteria [89]; [2]US EPA LCR Action Level [78].

2.3.1.3 Environmental air

Samples were collected at the refuse dump during e-waste burning events, however the results are not reported here as the samples quickly became over-loaded and were not able to be analyzed. As shown in Table 2-3, only five of the 13 metals measured in environmental air samples (n=23) had at least one sample concentration above the LOD. Of those, only one to three samples were above the LOD. An average of 441.8 L of air was collected during sampling of environmental air at a flow rate of 2.0 L per minute. Sb had a mean concentration (n=3) of 0.003 mg/m^3, while Cu had a mean concentration (n=3) of 0.005 mg/m^3. Both means are below the standards set by American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) of 0.5 mg/m^3 for Sb and 5 mg/m^3 for occupational exposures [90]. Taken together, these results show that some exposures, like those at or near burning activities, present a larger threat of exposure than manual dismantling.

Table 2-3 Environmental air samples (n=23) limits of detection and summary statistics from Thailand.

Metal[1]	Reference[2] (mg/m3)	N (%) > LOD	Mean (SD) (mg/m3)	Max (mg/m3)
Sb	0.5	3 (13.0)	0.003 (0.003)	0.02
Be	0.002	1 (4.3)	-	0.00006
Cu	1.0	3 (13.0)	0.005 (0.01)	0.05
Fe	-	1 (4.3)	-	0.003
Pb	0.05	2 (8.7)	-	0.01

[1]Cd, Cr, Co, Mn, Mo, Ni, V, and Z had no samples above the LOD and are therefore not reported.
[2]ACGIH TLV [90].

2.3.1.4 Rice

Seventeen rice samples were collected from Thailand as shown in Table 2-4. The number and percent (N(%)) above the limit of detection (LOD) are shown in the first column. The corresponding reference type and limit are given, as well as the N(%) of rice samples from Thailand above the reference limit for each metal. Although all 17 rice samples had values above the LOD for Cu, Fe, and Zn, none exceeded the corresponding reference limit. Approximately 20% of Cd and Pb samples exceeded the reference limit. These results suggest that workers and community members may be at risk of ingesting metals, perhaps from e-waste, in rice.

Table 2-4 Concentration of seven metals in rice samples from Thailand (n=17) with calculated reference values.

Metal	N (%) >LOD	Max (mg/kg)	Mean (mg/kg)	Reference Type	Reference Limit
Cd	8 (47.1)	1.1	0.1	ML[1]	0.2 mg/kg (MPL)
Cu	17 (100)	20.6	4.34	PMTDI[2]	0.5 mg/kg bw/day
Fe	17 (100)	149.9	36.9	PMTDI	0.8 mg/kg bw/day
Mn	17 (100)	104.4	36.3	TUIL[3]	11 mg/d
Ni	17 (100)	7.7	2.0	TUIL	1.0 mg/d
Pb	13 (76.5)	1.7	0.3	ML	0.2 mg/kg
Zn	17 (100)	34.1	29.8	PMTDI	2.1 mg/kg bw/d

[1]ML = Maximum Level [69]; [2] PMTDI = Provisional Maximum Tolerable Daily Intake [109]; [3]Tolerable Upper Intake Limit [74].

2.3.1.5 PBZ and area air

The results from personal and area air sampling are shown in Table 2-5. In Thailand, 46 PBZ and 27 area air samples were collected. In Chile, 15 area air samples were collected. Five participants from Chile and three from the Thailand occupational exposure group had repeat area air samples. Table 2-5 presents the results for all air samples collected, including duplicates. Mean values were calculated using each set of the repeated samples separately. The means between the two sets of values were not significantly different when we used the first sample or the second, and so the first sample was used for all further statistical tests where duplicates were not considered.

No samples from Thailand (PBZ or area) contained concentrations of Sb over the LOD, while 40% of samples from Chile had Sb concentrations over the LOD, with a mean concentration of 0.001 mg/m^3. Cu was detected in 15.2% of PBZ and 25.9% of area air samples from Thailand, while only 1 sample in Chile had Cu concentrations above the LOD. Fe was detected in samples from Thailand (PBZ and area) and Chile. The means between the three groups of air samples were significantly different for Fe ($p=0.007$). Only one sample, in the PBZ group from Thailand, exceeded the LOD for Pb. Finally, Zn was detected in all sample types. Overall, the results show low concentrations of metals in PBZ and area air samples from this study, and all samples were below occupational TLV limits set by ACGIH [90]. Additionally, there was a high percentage of samples with analyte concentrations below the LOD.

Table 2-5 Concentration of 13 metals in personal breathing zone and area air samples from Thailand and Chile.

		Personal Breathing Zone Samples				Area Air Samples							
		Thailand (n=46; average volume: 0.7 m^3)				**Thailand** (n=27; average volume: 1.3 m^3)				**Chile** (n=15; average volume: 1.0 m^3)			
Metal	**[2]Ref**	**N (%) >LOD**	**Mean (SD) (mg/m^3)**	**GM (GSD)**	**Max (mg/m^3)**	**N (%) > LOD**	**Mean (SD) (mg/m^3)**	**GM (GSD)**	**Max**	**N (%) >LOD**	**Mean (SD) (mg/m^3)**	**GM (GSD)**	**Max (mg/m^3)**
Sb	0.5	0	-	-	-	0	-	-	-	6 (40.0)	0.001 (0.0002)	-	0.002
Cu[1]	1.0	7 (15.2)	-	-	0.004	7 (25.9)	0.001 (0.001)	0.001 (0.001)	0.002	1 (6.7)	-	-	0.002
Fe[1]†*	-	39 (84.8)	0.07 (0.08)	0.003 (0.005)	0.04	27 (100)	0.004 (0.01)	0.004 (0.004)	0.04	13 (86.7)	0.01 (0.009)	0.005 (0.004)	0.002
Pb	0.05	0	-	-	-	1 (3.7)	-	-	0.001	0	-	-	-
Zn[1]	-	7 (15.2)	-	-	0.06	10 (37.0)	0.002 (0.003)	0.001 (0.001)	0.01	2 (13.3)	-	-	0.07

[1]A value of 1.0 was added to the concentrations prior to log transformation of the values. [2]ACGIH TLV [90]. †Indicates the sample means are significantly different using ANOVA ($p<0.05$). *Indicates sample means are significantly different using two-sample t-test (for same-country) ($p<0.05$). Metals with 0% >LOD not shown: Be, Cd, Cr, Co, Mn, Mo, Ni, V.

2.3.1.6 Surface wipes

Metal concentrations of food surface wipe samples collected in Thailand (n=37) and Chile (n=22) are displayed in Table 2-6. Mean Cu, Fe, and Zn concentrations were higher in Chile (approximately 5, 1.3, and 1.8 times higher, respectively) than in Thailand. However, the geometric means were similar for Cu, Fe, and Zn in Chile and Thailand. The maximum value for Fe in Chile was 18,000 µg/100 cm^2. This was not removed as an outlier as we believe the value to be correct and its inclusion did not affect statistical significance (see Figure 2-2). We observed a significant difference ($p<0.001$) between Thailand and Chile in the geometric mean concentration of Fe. Overall, work wipe samples had higher concentrations in Chile compared to Thailand.

Table 2-6 Concentration of 13 metals in food surface wipe samples in Thailand and Chile.

Metal	Thailand (n=37)					Chile (N=22)				
	N (%) > LOD	Mean (SD) (μg/100 cm²)	Med (μg/100 cm²)	GM (GSD)	Max (μg/100 cm²)	N (%) > LOD	Mean (SD) (μg/100 cm²)	Med (μg/100 cm²)	GM (GSD)	Max (μg/100 cm²)
Cr	1 (2.9)	-	-	-	13.0	1 (4.5)	-	-	-	45.0
Cu[1]	14 (40.0)	16.4 (20.5)	7.1	1.1 (0.3)	110.0	6 (27.3)	82.1 (204.2)	7.1	1.1 (0.7)	790.0
Fe	35 (100)	773.1 (894.4)	350.0	2.6*** (0.6)	3500.0	16 (72.7)	1012.0 (3817.7)	50.5	1.2*** (0.9)	18000.0
Pb	5 (14.3)	-	7.1	-	720.0	4 (18.2)	-	7.1	-	34.0
Mn[1]	18 (51.4)	19.2 (21.2)	7.1	1.1 (0.3)	110.0	3 (13.7)	-	7.1	-	110.0
Ni	1 (2.9)	-	7.1	-	21.0	1 (4.5)	-	7.1	-	36.0
Zn[1]	17 (48.6)	68.4 (150.8)	7.1	1.3 (0.6)	744.0	9 (40.9)	122.2 (466.8)	7.1	1.2 (0.6)	2100.0

***P<0.001. Sb, Be, Cd, Co, Mo, and V all had 0% of samples above the LOD and are therefore not reported.

Similar to Table 2-6, Table 2-7 displays the concentrations of wipe samples from work surfaces in Thailand (n=23) and Chile (n=16). Chile again had higher mean concentrations of Cu, Fe, and Zn (approximately 15, 10.8, and 8.9 times higher, respectively) compared with Thailand. We also saw very large maximum values in Chile (for example, Fe had a maximum value of 34,000 μg/100 cm^2). Chile had a significantly higher arithmetic mean and geometric mean concentrations of Pb compared to Thailand (approximately 95 and 1.9 times higher, respectively). Of note, the maximum Pb concentrations in Chile was 19,000 μg/100 cm^2. In sum, Chile had higher concentrations of metals in surface wipe samples for both food and work areas compared with Thailand.

Table 2-7 Concentration of 13 metals in work surface wipe samples in Thailand and Chile.

Metal	Thailand (n=23)					Chile (n=16)				
	N (%) > LOD	Mean (SD) (μg/100 cm²)	Med (μg/100 cm²)	GM (GSD)	Max (μg/100 cm²)	N (%) > LOD	Mean (SD) (μg/100 cm²)	Med (μg/100 cm²)	GM (GSD)	Max (μg/100 cm²)
Sb	0	-	-	-	-	1 (5.9)	-	-	-	32.0
Cd	0	-	-	-	-	3 (17.6)	-	-	-	13 .0
Cr	0	-	-	-	-	2 (11.8)	-	-	-	37.0
Cu	7 (30.4)	140.8 (601.8)	7.1	1.1 (0.6)	2900.0	11 (64.7)	2119.6 (4655.2)	63.0	2.1 (1.2)	18000.0
Fe	23 (100)	853.3 (1299.7)	350.0	2.6 (0.5)	5100.0	17 (100)	3822.5 (8180.4)	860.0	3.0 (0.8)	34000.0
Pb	5 (21.7)	19.4** (31.3)	7.1	1.0*** (0.4)	140.0	11 (64.7)	1847.9** (4732.5)	26.0	1.9*** (1.2)	19000.0
Mn	10 (43.5)	17.6 (21.2)	7.1	1.1 (0.3)	76.0	9 (52.9)	24.8 (26.8)	17.0	1.2 (0.7)	110.0
Ni	2 (8.7)	8.0 (3.3)	7.1	0.9 (0.1)	21.0	7 (41.2)	15.2 (12.7)	7.1	1.1 (0.3)	45.0
Zn	6 (26.1)	40.4*** (70.4)	7.1	1.7* (0.6)	234.0	15 (88.2)	359.9*** (473.1)	240.0	2.1* (0.8)	1900.0

**p<0.01; ***p<0.001. Be, Co, Mo, and V all had 0% of samples above the LOD and were therefore not reported.

Significant differences between food and work surface wipe samples, as well as significant difference between the same type of wipe sample between countries, are displayed in Figure 2-2. Concentrations of some metals, including Pb, were notably higher in work surface samples than food areas; however, statistical tests could not be performed due to a large percentage of the samples below the limit of detection in food samples. These are therefore not reflected in Figure 2-2. There were significant differences in Chile between work and surface area concentrations of Cu, Fe, and Zn (the three metals for which we were able to calculate a mean for in Chile's food surface wipe samples); however, we did not see the same significant differences in wipe sample types in Thailand. A non-significant p-value (p=0.07) is shown in Figure 2-2a for work samples because it is very near the alpha-value of 0.05 and may be important to consider in future studies.

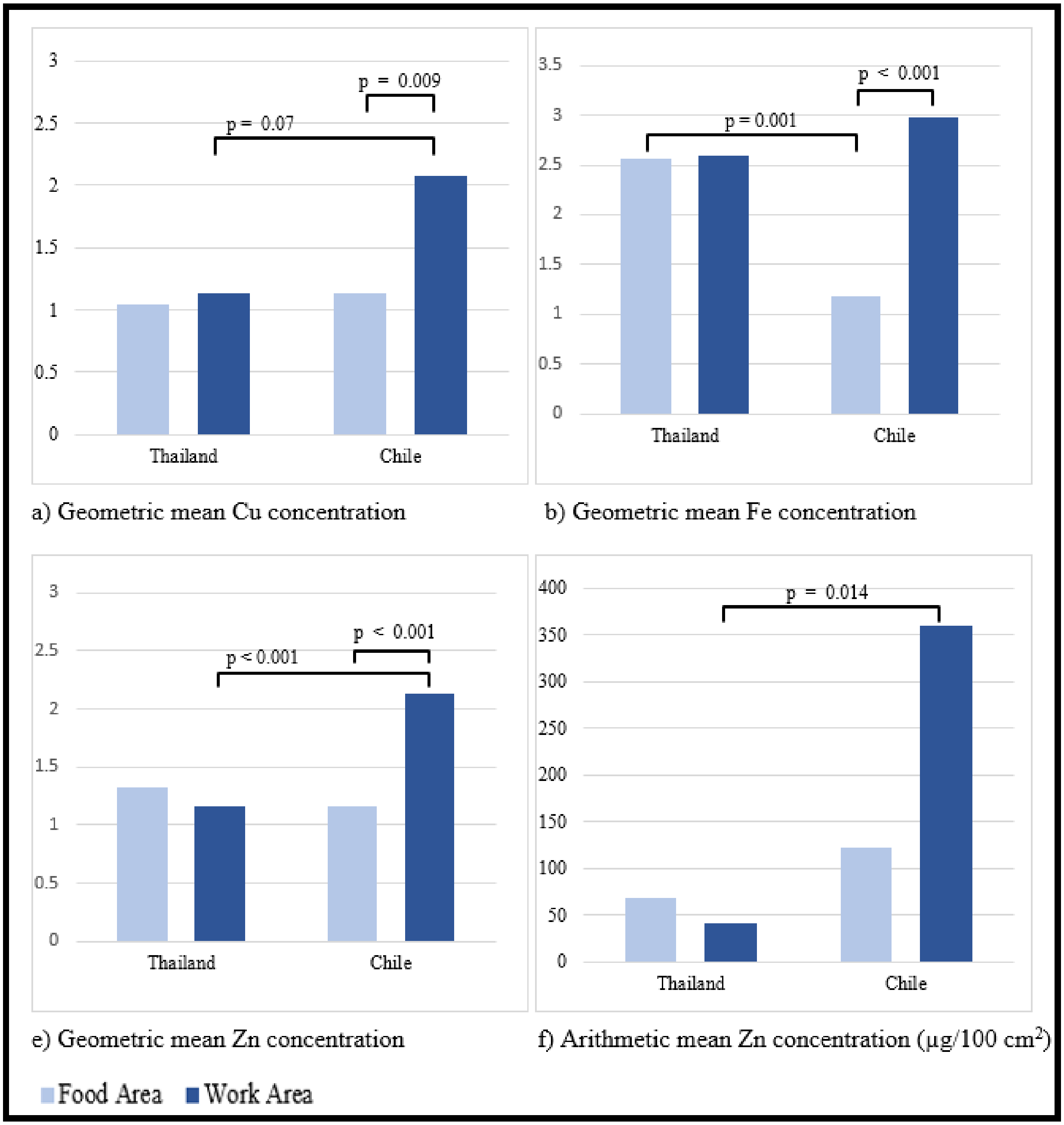


Figure 2-2 Results of independent samples t-test between arithmetic and geometric means of metal concentrations in surface wipe samples.

2.3.2 Demographic results

From our Thai research community, we recruited 130 e-waste workers and 53 community members. From Chile, we recruited 95 e-waste workers. Demographics for each of the three groups are shown in Table 2-8. There was a significant difference ($p<0.001$) in residence time between the three groups, with the Thai occupational group residing in the same community for the longest period of time (average of 51.9 years) and the Chilean occupational group the shortest time (14.4 years). There was also a significant difference in the average number of years working in e-waste (t-test between occupational groups, $p<0.005$) with Thailand having a mean of 16.8 years and Chile having a mean of 12.4 years. Sex was also significantly different between the three comparison groups, with the Chilean occupational group having the highest proportion of males (73.1%), and the Thai community group the smallest (25.0%).

The incomes for each country were compared to the minimum wage. The income categories on the survey did not match up exactly with minimum wage levels, and so a few participants in each country may incorrectly be categorized as below minimum wage. Finally, questions about cigarette use were considered culturally insensitive in at least one of our sample groups, and so these questions were omitted from our analysis.

Table 2-8 Demographic data for the three exposure populations (Thailand community, Thailand occupational, and Chile Occupational).

	Thailand Community		Thailand Occupational		Chile Occupational	
Variable	**N**	**Mean (sd)**	**N**	**Mean (sd)**	**N**	**Mean (sd)**
Age (years)	44	49.3 (9.5)	130	51.2 (4.9)	93	46.8 (14.3)
Residence time (ys)	14	43.3 (10.5)	125	51.9 (81.5)	93	14.4 (15.1)***
E-waste time (years)	NA	NA	120	16.8 (11.9)	92	12.4 (11.8)**
BMI (kg/m^2)	28	23.5 (4.0)	69	24.9 (4.2)	93	30.1 (5.8)**
	N	**N (%)**	**N**	**N (%)**	**N**	**N (%)**
Sex - Male	53	12 (22.6)***	130	71 (54.6)***	93	68 (73.1)***
Marital status - Single	42	3 (5.7)**	130	9 (6.9)**	87	19 (21.8)**
-Married		29 (54.7)		115 (88.5)		58 (66.7)
-Divorced		2 (3.8)		2 (1.5)		1 (1.1)
-Cohabitating		3 (5.7)		0		3 (3.4)
-Widowed		5 (9.4)		4 (3.1)		3 (3.4)
-Separated		0		0		3 (3.4)
Education – None	39	0***	127	7 (5.5)***	93	7 (7.5)***
-Primary		32 (82.1)		57 (44.9)		30 (32.3)
-Secondary		7 (18.0)		48 (37.8)		41 (44.1)
-Some college		-		15 (11.8)		15 (16.1)
Income > min wage	41	9 (17.0)***	130	49 (37.7)***	87	55 (63.2)***
Second-hand smoke	27	17 (32.1)	36	10 (7.7)	93	31 (33.3)

**$p<0.01$; ***$p<0.001$

2.3.3 Biomarker results

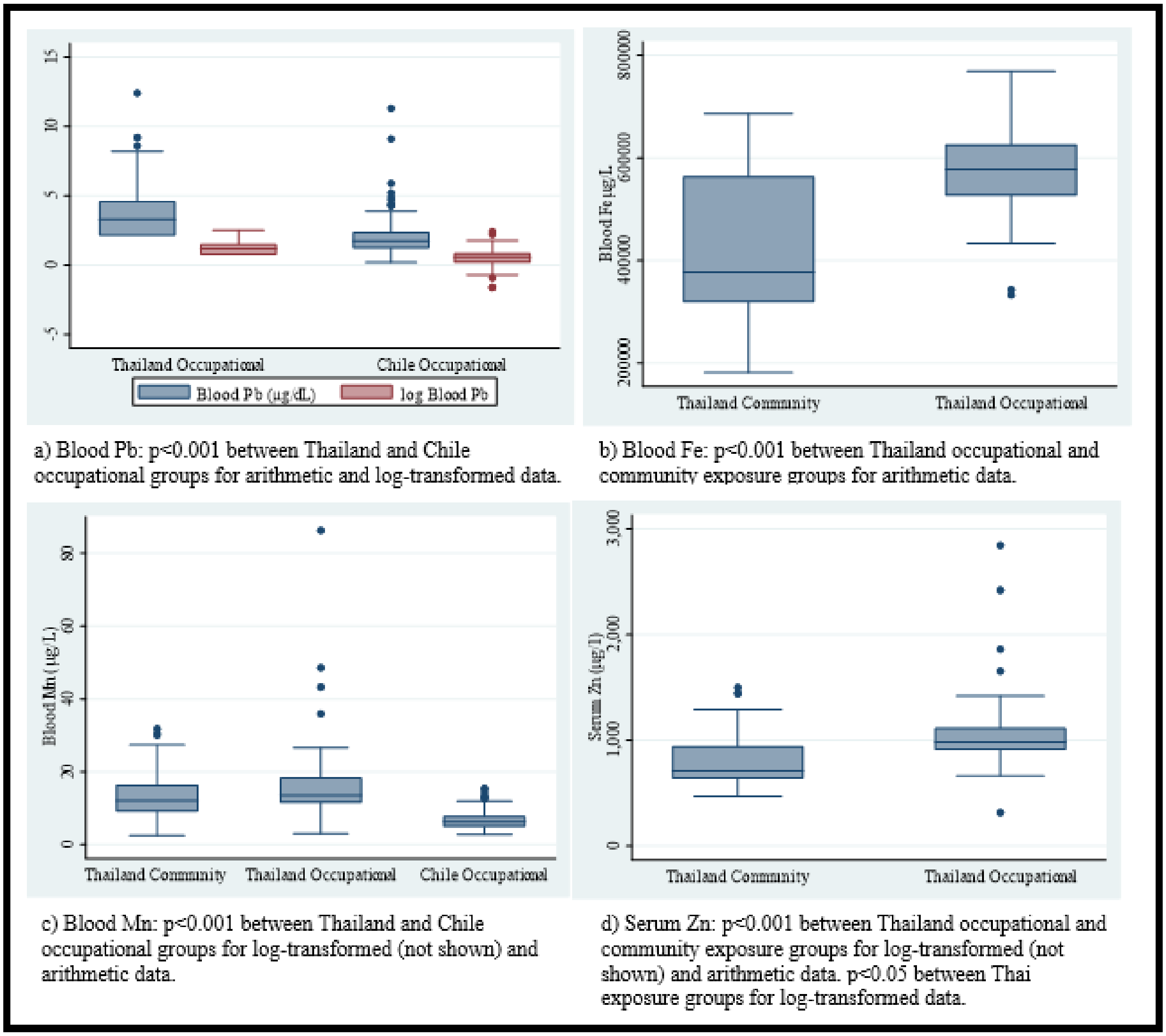
Results of the biomarker analyses are shown in Table 2-9. From the Thailand Community exposure group, 46 participants provided blood/serum samples and 47 participants provided urine samples. From Thailand's Occupational exposure group, 105 blood/serum samples and 116 urine samples were collected. Finally, from Chile's Occupational exposure group, a total of 86 blood/serum and 82 urine samples were collected. Blood Al and urinary Mn were dropped from the Thai dataset and analysis due to a high blank concentration, which resulted in negative blank-adjusted values. The Thailand community exposure group had a higher concentration of urinary Cd than the Thailand occupational reference group. All other biomarkers had a higher mean concentration in the occupational exposure group compared to the community group in Thailand. From the Chilean occupational exposure group, several biomarkers, including blood Al, Fe, Ni and serum Cu, Zn were not analyzed due to data quality issues at the analyzing laboratory in

Thailand. The Chile exposure group had 0.6 times lower mean concentrations of blood Pb, and 0.4 times lower concentration of blood Mn but 1.1 times higher blood Cd concentration compared with the Thai occupational group.

Table 2-9 Concentrations of metals in blood and urine of the occupational exposure group in Chile and Thailand, and in the community exposure group in Thailand.

Exposure Group	Blood & Serum					Urine (creatinine adjusted)				
Thailand – Community (n=46)						**(n=47)**				
	LOD	**n(%)>LOD**	**Mean (SD) (µg/L)**	**GM (GSD)**	**Max (µg/L)**	**LOD**	**n(%)>LOD**	**Mean (SD) (µg/g)**	**GM (GSD)**	**Max (µg/g)**
Al[1]	-	46 (100)	-	-	-	0.456	47 (95.7)	36.1 (59.7)	2.6 (1.6)	265.3
Cd[3]	1.0	14 (30.4)	0.9 (0.4)	0.6 (0.2)	2.0	0.004	47 (100)	0.5 (0.8)	0.3 (0.4)	4.7
Fe[3]	-	46 (100)	420239.3 (133922.8)	NA	686371.0	0.093	47 (100)	54.7 (101.7)	2.5 (2.0)	550.3
Pb[2,3]	3.0	8 (17.4)	-	-	5.4	0.015	32 (68.1)	3.1 (6.6)	0.7 (1.0)	38.5
Mn	5.0	46 (100)	13.8 (6.6)	2.5 (0.5)	31.8	0.005	20 (42.6)	-	-	-
Ni[3]	0.537	17 (37.0)	-	-	-	0.072	45 (95.7)	2.9 (4.6)	01.0 (0.8)	27.1
Serum										
Cu	1.000	46 (100)	1049.8 (241.3)	6.9 (0.2)	1842.6	0.013	16 (34.0)	12.6 (12.2)	2.2 (0.9)	62.2
Zn	1.252	46 (100)	806.6 (263.9)	6.7 (0.3)	1499.1	0.151	42 (89.4)	363.9 (300.4)	5.4 (1.5)	1464.8
Thailand – Occupational (n=105)						**(n=116)**				
	LOD	**n(%)>LOD**	**Mean (SD) (µg/L)**	**GM (GSD)**	**Max (µg/L)**	**LOD**	**n(%)>LOD**	**Mean (SD) (µg/g)**	**GM (GSD)**	**Max (µg/g)**
Al[1]	NA	105 (100)	-	-	--	0.456	116 (100)	52.5[1] (54.8)	3.7 (0.9)	436.0
Cd	1.0	29 (27.6)	1.0 (0.5)	0.7 (0.2)	3.10	1.000	2 (1.7)	-	-	0.9
Fe[3]	-	105 (100)	579670.0 (81686.6)	-	769171.0	-	116 (100)	106.2 (134.3)	4.2 (1.0)	842.2
Pb[2,3]	3.0	64 (61.0)	3.8 (2.0)	1.2 (0.5)	12.4	0.005	115 (99.1)	7.5 (7.4)	1.8 (0.8)	41.4
Mn	3.0	105 (100)	15.9 (9.5)	2.7 (0.4)	86.2	0.537	-	-	-	-
Ni[3,4]	0.537	105 (100)	-	-	-	0.229	116 (100)	5.0 (3.8)	1.6 (0.6)	19.4
Serum										
Cu[5]	1.000	105 (100)	1095.1 (295.0)	7.0 (0.2)	2740.5	0.693	116 (100)	23.6 (38.8)	2.8 (0.8)	370.3
Zn	1.252	105 (100)	1044.2 (295.9)	6.9 (0.2)	2844.5	0.590	116 (100)	671.1 (501.2)	6.3 (0.8)	3328.8
Chile – Occupational (n=86)						**(n=82)**				
	LOD	**n(%)>LOD**	**Mean (SD) (µg/L)**	**GM (GSD)**	**Max (µg/L)**	**LOD**	**n(%)>LOD**	**Mean (SD) (µg/g)**	**GM (GSD)**	**Max (µg/g)**
Al[1]	-	-	-	-	-	-	-	-	-	
Cd	1.0	85 (98.8)	1.1 (0.8)	0.7 (0.3)	4.6	0.004	82 (100)	0.3 (0.2)	0.2 (0.2)	1.2
Fe[3]	-	-	-	-	-	0.093	64 (78.0)	7.1 (8.1)	1.6 (1.2)	49.5
Pb[2,3]	3.0	81 (94.1)	2.2 (1.7)	0.5 (0.7)	11.3	0.015	72 (87.8)	1.4 (1.5)	0.7 (0.5)	9.7
Mn	5.0	86 (100)	6.9 (2.9)	1.9 (0.4)	15.5	0.005	82 (100)	1.4 (1.1)	0.1 (0.7)	5.7
Ni[3]	-	-	-	-	-	0.072	78 (95.1)	2.8 (5.1)	1.0 (0.7)	38.6
Serum										
Cu	-	-	-	-	-	0.013	82 (100)	9.6 (6.7)	2.1 (0.5)	51.6
Zn	-	-	-	-	-	0.151	82 (100)	257.2 (189.1)	5.3 (0.8)	948.7

[1]One outlier removed (1336.3 µg/g) because inclusion resulted in a significant t-test and more than doubled the standard deviation. [2]Shown in µg/dL. [3]A value of 1.0 was added to the urine concentrations (µg/g) prior to log transformation of the values. [4]Six negative values from the Thai occupational group removed. [5]Two negative values from the urine from Thai occupational group removed NA indicates cells that are empty due to la normally-distributed sample.



a) Blood Pb: p<0.001 between Thailand and Chile occupational groups for arithmetic and log-transformed data.

b) Blood Fe: p<0.001 between Thailand occupational and community exposure groups for arithmetic data.

c) Blood Mn: p<0.001 between Thailand and Chile occupational groups for log-transformed (not shown) and arithmetic data.

d) Serum Zn: p<0.001 between Thailand occupational and community exposure groups for log-transformed (not shown) and arithmetic data. p<0.05 between Thai exposure groups for log-transformed data.

Figure 2-3 Box plots showing statistically significant relationships between exposure groups in mean concentration of blood and serum biomarkers.

Significant differences in blood and serum biomarkers are shown in **Error! Reference source not found.**. There was a significant difference between the mean concentrations in Thailand and Chile occupational groups for blood Pb and Mn, as well as the geometric mean concentrations of blood Pb and Mn. Between the two Thailand exposure groups, there was a significant difference in the arithmetic concentrations of blood Fe and serum Zn, as well as the geometric mean of serum Zn. Some differences could not be used for tests of significance due to a low % of samples <LOD. Therefore, some important differences, like the difference in blood

Pb concentrations between the Thai occupational and community exposure groups, are not reflected in the significant relationships found in **Error! Reference source not found.**.

Significant differences between the three exposure groups were tested among urinary biomarkers through the same t-test methods described for **Error! Reference source not found.**. The results are displayed in the boxplots of

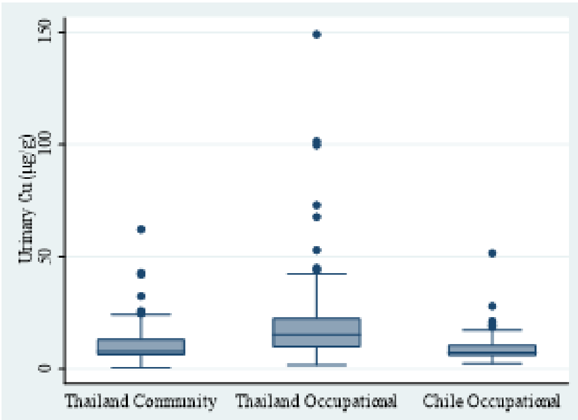
Figure 2-4. Between the Thailand and Chile occupational exposure groups, there was a significant difference in the arithmetic and geometric mean concentrations of urinary Cu, Fe, Pb, Zn, and Ni. Between the Thailand community and occupational exposure groups, there were also significant differences between the arithmetic and geometric mean concentrations of urinary Cu, Fe, Pb, Zn, and Ni. There were no significant differences between the two groups for the arithmetic and geometric mean urinary Al concentrations. There were no significant differences between the two Thailand exposure groups nor the two occupational exposure groups with respect to urinary Cd because the Thailand occupational exposure groups did not have enough samples above the limit of detection to calculate arithmetic or geometric mean concentrations.

Table 2-10 Available reference values for metal biomarker concentrations in adults.

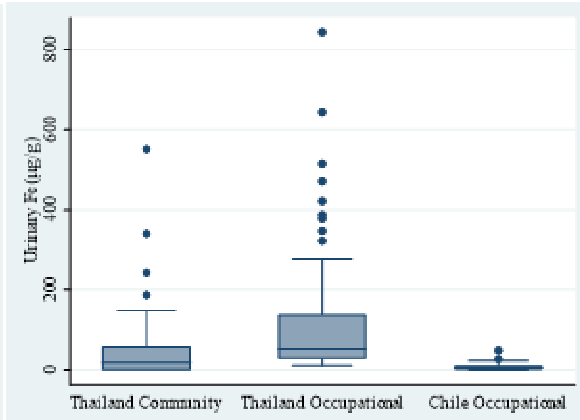
Metal	**Whole Blood (µg/L)**	**Urine (µg/g)**
Al	N/A	N/A
Cd	5.0[1]	5.0[1]
Fe	N/A	N/A
Pb	30.0[1] µg/dL	0.5[2]
Mn	14-16[3]	N/A
Ni	1.1[3]	4.4[3]
	Serum (µg/L)	
Cu	151.6[4]	25[3]
Zn	N/A	1100[3]

[1]ACGIH BEI [90]; [3]NHANES [126]; [4]CHMS [92]; [5]ATSDR [93];

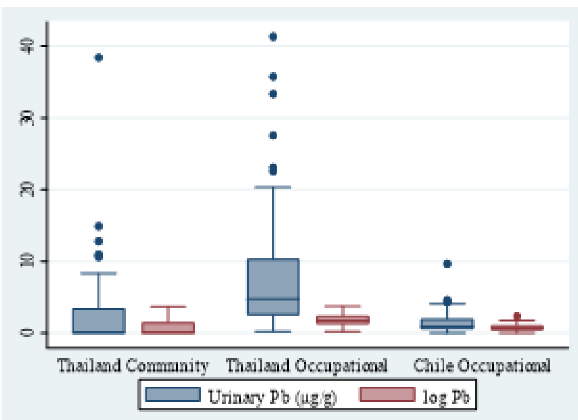
Compared with the community exposure group in Thailand and the occupational exposure group in Chile, the occupational exposure group in Thailand had higher concentrations of all biomarkers except for blood Cd, for which Chile had the highest mean concentration, and urinary Cd, for which the Thai community group had the highest mean concentration. Available reference values are shown in Table 2-10. All of the exposure groups had mean and maximum concentrations below these BEI values. The maximum value for both occupational exposure groups did not exceed the National Institute of Occupational Safety and Health (NIOSH)'s reference value of 30.0 µg/dL for blood Pb [90], but did exceed the CDC's blood lead reference value of 10.0 µg/dL for healthy adults [94]. Compared with the National Health and Nutrition Examination Survey (NHANES) study group of healthy adults, where the average urinary Pb concentration was 0.5 µg/g, the Thai community group was 6.2 times higher, the Thai occupational group was 15 times higher, and the Chilean occupational group was 2.8 times higher [91].



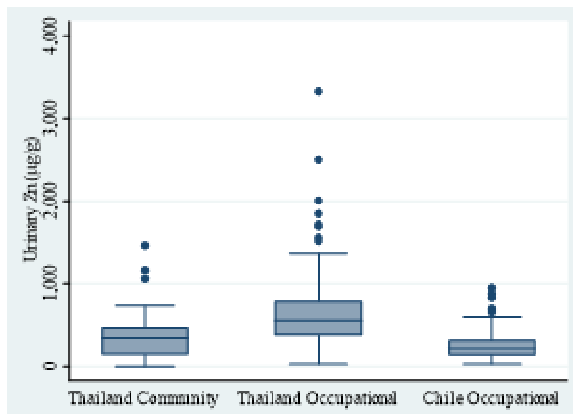
a) Urinary Cu: p <0.001 between Thailand occupational and community exposure groups for log-transformed data (not shown). p<0.001 for arithmetic and log-transformed data between Thailand and Chile occupational groups.



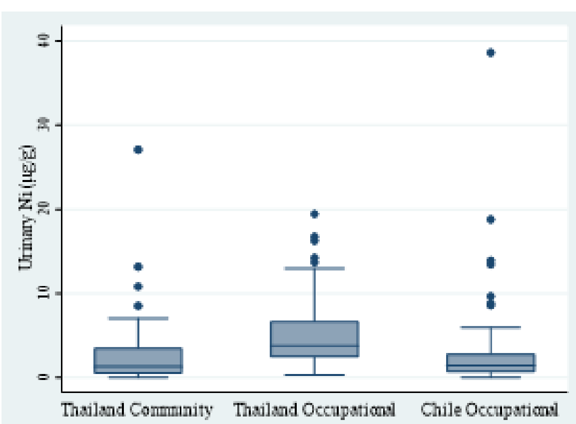
b) Urinary Fe: p<0.001 between Thailand occupational and community exposure groups for log-transformed data (not shown). p<0.001 for arithmetic and log-transformed data between Thailand and Chile occupational groups.



c) Urinary Pb: p <0.001 between Thailand occupational and community exposure groups for arithmetic and log-transformed data (not shown). p<0.001 between Thailand and Chile occupational exposure groups for log-transformed and arithmetic data.



d) Urinary Zn: p<0.001 between Thailand occupational and community exposure groups for arithmetic and log-transformed (not shown) data. p<0.001 for arithmetic and log-transformed data between Thailand and Chile occupational groups.

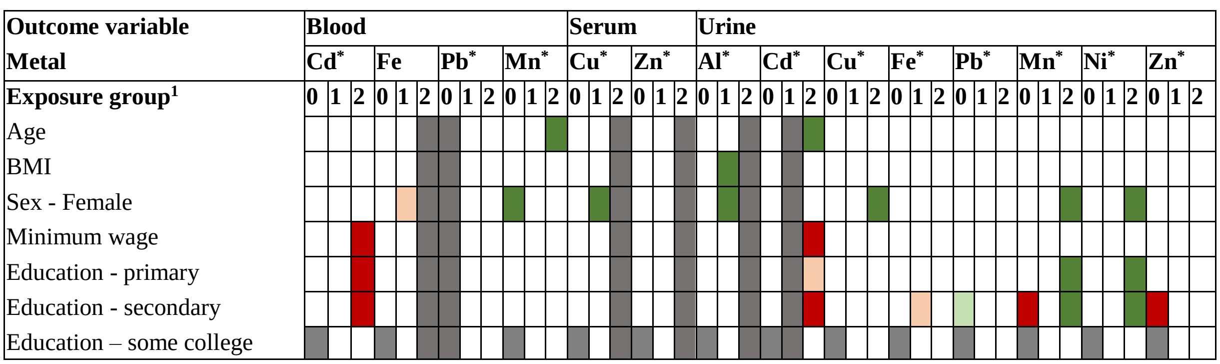


f) Urinary Ni (left): p<0.05 between Thailand occupational and community exposure groups for arithmetic data, and p<0.001 for log-transformed (not shown) data. p=0.001 for arithmetic data between Thailand and Chile occupational groups and p<0.001 for log-transformed data.

Figure 2-4 Box plots showing statistically significant relationships between exposure groups in mean concentration of urine biomarkers.

2.3.4 Regression model results

Results of regressions run for each exposure group with the outcome variable as a biomarker and with demographic variables as co-variates are displayed in Figure 2-5. Covariates with a significant positive coefficient are shown in green, and significant negative coefficients are shown in red. Marginally significant (0.05<p<0.059) coefficients are shown in lighter shades, as these have the potential to become significant if the model were to be adjusted. For example, secondary education was a marginally significant (p=0.051) predictor for urinary log Fe among the Thailand occupational exposure group and became significant (p=0.049) when the minimum wage income predictor was removed. Secondary education was a marginally significant (p=0.052) predictor for urinary log Pb and became significant (p=0.047) when the predictor variables sex, and age were removed from the model.



*Indicates the log-transformed data was used. [1]Group 0 = Thailand community; Group 1 = Thailand occupational; Group 2 = Chile occupational.

- Significant (p<0.05) positive coefficient
- Significant (0.05<p<0.059) positive coefficient
- Significant (p<0.05) negative coefficient
- Significant (0.05<p<0.059) negative coefficient
- Exposure group is missing the indicated biomarker, or the number of uncensored samples were <20%.

Figure 2-5 Selected demographic variables and their strengths of association with biomarker outcome variables.

The heat map in Figure 2-5 shows a trend for female participants to have higher concentrations of log metals in all but log Fe in models where sex was a significant predictor. Education was a significant predictor in several models; however, there was inconsistency in the direction of the coefficient. The numerical value of significant coefficients for the regressions shown in the heat map are displayed in **Error! Reference source not found.**.

Table 2-11 Coefficients for significant demographic variables in regression models for the three exposure groups.

Exposure Group	Biomarker	Constant	Age	BMI	Sex - Female	Minimum wage	Education – 1º	Education – 2º	Education – SC	Adj R^2
	Blood									
Thai Occup	Log Cd	1.162*	0.003	-0.005	0.046	-0.388**	-1.03**	-0.908*	-0.798*	0.166
Thai Comm	Log Mn	1.508	-0.008	0.029	0.812*	0.153	NA	-0.254	NA	0.149
Thai Occup	Log Mn	1.582	0.418*	-0.015	0.079	0.116	0.106	0.294	0.341	0.078
	Serum									
Chile Occup	Log Cu	6.854	-0.002	0.006	0.129*	-0.022	NA	-0.025	NA	0.086
	Urine									
Chile Occup	Log Al	5.751***	-0.015	-0.053*	0.459*	-0.516	NA	-0.414	NA	0.117
Thai Occup	Log Cd	0.533**	0.004*	-0.008	0.125**	-0.123**	-0.221	-0.202	-0.177	0.272
Thai Occup	Log Cu	1.076*	0.006	0.022	0.317*	-0.161	0.158	-0.067	0.052	0.152
Thai Comm	Log Mn	4.65	-0.030	-0.123	0.264	1.153	NA	-2.266*	NA	0.015
Thai Occup	Log Mn	-1.577*	0.012*	0.001	0.504**	-0.133	1.157*	0.982*	0.578	0.256
Thai Occup	Log Ni	-4.643**	0.023	0.032	0.833*	-0.375	3.110**	2.623*	1.930	0.243
Thai Comm	Log Zn	4.851*	0.002	0.026	-0.2994	0.170	NA	-1.013*	NA	0.115

Thai Comm = Thailand community; Thai Occup = Thailand occupational; Chile Occup = Chile occupational. SC = Some college. NA: Only 2 categories represented by exposure group. *p<0.05, **p<0.01, ***p<0.001.

Two models were further developed to determine which, if any, demographic variables explained differences in blood and urine concentrations observed among the Chile occupational group. Results are displayed in Tables B-1 and B-2 of Appendix B. Differences in log blood Cd concentrations were significantly negatively correlated with income above the minimum wage, and higher levels of education. Urinary concentrations of log Cd were significantly negatively correlated with income over the minimum wage, and significantly positively correlated with being female and age.

Three models were also developed for the three biomarkers with significant predictors among the non-occupational exposure group in Thailand. The results can be found in Tables B3-B5 of Appendix B. Female sex was a positive significant predictor of log blood Mn, and having a secondary education was marginally significant for a negative association with log urine Mn. In model 2 of Table B-4, education was significant but becomes less significant when minimum wage was removed from the model. Because the unadjusted coefficient for education changed by 11% between models 2 and 3, there was evidence for potential confounding of the effect of education on urinary log Mn concentrations by wage. Finally, Table B-5 shows model development for the log urinary Zn concentrations among the Thai community group. Model 3 shows that both having a secondary education or higher and being female were negatively significantly associated with log urinary Zn concentrations.

2.3.5 Method of Triads results

By definition, three measures of exposure are needed in order to apply the Method of Triads. **Error! Reference source not found.** shows the counts for the number of samples collected by sample type for each of the three exposure groups. Due to logistical and financial limitations, there was not a wipe, biomarker, and air sample collected for every study participant. The bottom row, “3 or more”, is the number of participants for which three or more sample types were available and is thus the number of participants in each group eligible to be included in the Method of Triads analysis.

Table 2-12 Sample counts by exposure group for use in method of triads analysis. Note that 3 or more sample types for an individual participant are needed to apply the method of triads.

Samples	**Thailand – Community**	**Thailand – Occupational**	**Chile – Occupational**
Participants (Total)	47	130	95
Blood	46 (97.9)	105 (80.8)	82 (86.3)
Urine	47 (100)	116 (89.2)	86 (90.5)
Wipe - Food	18 (38.3)	43 (33.1)	45 (47.4)
Wipe – Work	17 (36.2)	41 (31.5)	43 (45.3)
Air – Personal	0	32 (24.6)	0
Air – Area	11 (23.4)	7 (5.4)	35 (36.8)
3 or more sample types	24 (51.1)	45 (34.6)	53 (55.8)

All two-way Spearman correlation coefficients are listed in Table B-6 of Appendix B, which also includes the sample size for each statistical test. The results of the Method of Triads are displayed in Table 2-13. Seventeen percent of validity coefficients were greater than one (e.g., Heywood cases [95]) and were dropped. Of 110 sample combinations for which Spearman correlation coefficients were calculated, 40% had negative correlation coefficients and were dropped from further use in the Method of Triads calculations (See Appendix B, Table B-6). Between work wipe, urine, and serum samples, work wipe samples had the highest validity. Similarly, for food wipe, urine, and serum samples, the most valid estimate of Cu exposure was food wipe samples. Between food wipe, work wipe, and serum samples, food wipes had the highest validity for Cu. Between food wipe, work wipe, and urine samples, work wipes had the highest validity for Cu. When comparing food wipe, area air, and urine samples, urine was the most valid measure of exposure for Zn. Out of six sets of three validity coefficients, food wipes had the highest validity coefficient in 50% of cases, work wipes in 33% of cases, urine in 17% of cases, and serum and area air samples in 0% of cases.

Table 2-13 Spearman correlation coefficients between exposure and biomarker samples and the validity coefficient determined by the method of triads for electronic waste workers stratified by exposure group.

Metal	Exp Group	ρ_1	ρ_2	ρ_3	VC1TX	VC2TX	VC3TX
		Work*Serum	**Work*Urine**	**Serum*Urine**	**Work wipe**	**Serum**	**Urine**
Cu	Thai Comm	0.218	0.470	0.193	0.729	0.299	0.645
Zn	Thai Comm	0.030	0.300	0.626	0.120	0.250	H
Zn	Thai Occup	0.010	0.100	0.152	0.081	0.123	H
		Food*Serum	**Food*Urine**	**Serum*Urine**	**Food wipe**	**Serum**	**Urine**
Cu	Thai Comm	0.553	0.255	0.193	0.855	0.646	0.298
Zn	Thai Comm	0.048	0.017	0.626	0.015	H	0.471
		Food*Serum	**Work*Serum**	**Food*Work**	**Food wipe**	**Work wipe**	**Serum**
Cu	Thai Comm	0.553	0.218	0.284	0.849	0.335	0.652
Zn	Thai Comm	0.048	0.030	0.661	H	0.064	0.047
		Food*Urine	**Work*Urine**	**Food*Work**	**Food wipe**	**Work wipe**	**Urine**
Cu	Thai Comm	0.255	0.470	0.284	0.393	0.723	0.650
Mn	Thai Occup	0.001	0.203	0.042	0.014	H	0.070
Mn	Chile Occup	0.052	0.002	0.012	0.559	0.021	0.029
Zn	Thai Comm	0.017	0.300	0.661	0.088	0.194	H
		Food*Area Air	**Food*Urine**	**Area Air*Urine**	**Food wipe**	**Area Air**	**Urine**
Zn	Chile Occup	0.11	0.08	0.19	0.15	0.34	0.55

Thai Comm = Thailand community; Thai Occup = Thailand occupational; Chile Occup = Chile occupational. Food = food surface wipe sample; Work = work surface wipe sample; *r* denotes the correlation between two sample types. VC = the coefficient of variation corresponding to the sample type listed directly above the value in the table. TX = the "true" concentration of metal X, corresponding with the metal listed in the left-most column. H = Heywood case. [1]Serum; otherwise whole blood biomarker.

2.4 Discussion

This study examined the concentration of metals in environmental media (soil, rice, water, air, surface dust wipes) and human blood and urine biomarkers. The Method of Triads was then used to determine which type of sample was the best estimate of the true, unknown exposure. This study is novel in several ways. First, it is the first study to compare biomarker concentrations in e-waste worker groups from two geographically and culturally distinct locations. Secondly, the extensive sampling of media from the Thai community, including environmental and human groups, allows for a deeper understanding of which routes of exposure are important for human health. Finally, the application of the Method of Triads to samples of environmental and biological media is innovative for assisting future sample media selection.

2.4.1 Environmental samples

Some samples of rice, water, and soil all had concentrations of Pb above limits designed to protect human health. This indicates that environmental exposures to Pb from e-waste are a concern to workers and non-workers in the Thai community where research was conducted.

2.4.1.1 Soil

Several environmental samples had elevated concentrations of metals. As demonstrated in Table 2-1, the soil samples from the Thai research site had mean concentrations of Cd, Cu, Pb, and Zn that exceeded the recommended reference values, with only Ni having a lower value than the Dutch Target Value. When compared to the concentrations of metals from studies in other e-waste sites in Ghana and in China [88] (Table 2-1), the soil samples from the Thai study site had lower concentrations of Cd, Cu, and Pb compared to Ghana, but higher levels of Zn. The Thai study site had higher levels of Cd and Mn than were observed in China, but lower levels of Pb. Of particular concern, due to their impact on human and ecological health, are Pb and Cd. Cd can enter into paddy soil and rice through several routes in addition to e-waste recycling, including application of Cd-containing fungicides and fertilizers, and so e-waste recycling may not be the only or even the primary source of soil Cd [96]. The concentrations of metals in the soil of the Thai research site, particularly lead, are concerning.

2.4.1.2 Rice

The elevated concentration of some metals in soil was reflected in rice samples, with 17.5% of rice samples having Cd levels over the reference limit, and 23.5% of samples exceeding the Pb reference limit [69]. Fu et al., 2008 examining rice in an e-waste site in China found a mean concentration of Cd double that measured in our study [97]. The same study reported a mean Pb concentration nearly ten times higher than our results. A second study of rice by Zhang et al., 2013 from an e-waste site in China reported higher mean concentrations of Cd but lower concentrations of Pb compared to our study (0.44 mg/kg, 0.2 mg/kg, respectively) [28]. Several rice samples in this study exceeded the TUIL for Mn and Ni [71]. The concentrations for these metals exceeded those found in Fu et al., 2008, which reported a mean concentration of Mn as 28.64 mg/kg and Ni as 0.76 mg/kg [97]. Zheng et al, 2013 [28] also reported a lower mean concentration of Ni compared with our results (1.33 mg/kg). The results suggest that rice grown near the Thai study site is at risk of metal contamination. Although Cd concentrations appear to be lower than other e-waste areas, Pb, Ni, and Mn concentrations were similar or higher than found in comparable studies from e-waste sites in China. Workers and community members are exposed to metals through ingestion of locally-grown agricultural products.

2.4.1.3 Surface water

Mean (0.04 mg/L) and maximum (0.4 mg/L) values for Cd in surface water were above the EPA AWQC level; however, only 57.1% of samples were above the LOD. No measurements from the community water samples (>1 km from e-waste burn site) had Cd concentrations above the LOD. These concentrations are less than those reported in a study of water in two surface ponds near an e-waste site in China (1.66 and 1.59 mg/L) [31]. The same study had mean Cu concentrations (31.1 and 55.1 mg/L) well above the mean Cu concentration found in this study (0.9 mg/L in refuse dump samples). However, this study had a higher mean Pb concentration in the refuse dump samples (0.3 mg/L) compared with Wu et al, 2015 (0.10 and 0.12 mg/L) [31]. The mean concentration of Pb in refuse dump samples is 15 times larger than that of the reference value of 0.02 mg/L set by the US EPA lead and copper rule for drinking water. The results show that surface water samples near the refuse dump, where e-waste is burned and occasionally recycled, had higher mean concentrations of Cd, Cu, and Pb compared to samples taken more than 1 km from the e-waste site. The elevated Pb concentration might be in part explained by the recycling of CRT glass which occurs at the refuse dump. These results suggest that e-waste recycling activities at the dump site are contaminating the water with metals.

2.4.1.4 Environmental air

It is possible that dismantling activities create localized air pollution rather than exposures that would be found in community areas away from e-waste recycling activities. The fact that our air samples collected during burning events at the e-waste refuse dump were overloaded suggests that workers near the burning plumes in the refuse site may have higher exposures than those described in our results. Exposures to smoke plumes from e-waste presents an occupational and public health hazard.

2.4.1.5 PBZ and area air

Collection of air samples in the direct vicinity of e-waste dismantling activity, including PBZ and area air samples, revealed detectable concentrations of Cu, Fe, and Zn in both Thailand and Chile. Sb concentrations above the LOD were found in 40% of samples in Chile. More communications technology e-waste was observed in Chile, and Sb is a component of the circuit boards used in communications devices [98]. A study examining the concentration of metals in PBZ samples from the formal sector had a substantially higher geometric mean concentration of Fe (66.0) compared to the PBZ samples from Thailand (0.003). Between the PBZ and area air samples in Thailand, Fe was the only metal for which means could be compared using a t-test, for which the means were significantly different ($p<0.05$). Chile had a higher mean concentration of Fe (0.7 mg/m^3) in area samples compared to Thailand (0.1 mg/m^3). The concentration was higher in the PBZ compared to the area air sample. These results are consistent with methodological studies that report an increase in trace element concentrations in PBZ samples over static samples [99], [100]. When feasible, PBZ sampling techniques should be used to measure e-waste worker exposure to metals. Our results showed that exposures to metals suspended in air during dismantling were below concentrations recommended to protect human health.

2.4.1.6 Surface wipe

Food wipe samples in Thailand had a higher mean concentration of Cu and lower mean concentrations of Fe and Zn compared to Chile. The maximum concentration of Pb in both countries exceeded the EPA's dust sample standards for houses (Floors: 4.3 μg/100 cm^2; windowsills: 26.9 μg/100 cm^2). There are no other studies of food surface areas in e-waste areas with which to compare these results. Among work wipe samples, Thailand had higher mean concentrations for all metals for which there are comparable values (Cu, Fe, Pb, Mn, Ni, and Zn). Chile had significantly higher arithmetic mean concentrations in work wipe samples for all three metals for which there were comparable means in food samples (Cu, Fe, Zn), while Thailand did not show any significant differences between food and work wipe mean concentrations. Other studies from e-waste shops in China have also found concentrations of Cd, Cu, Pb, Ni and Zn in dust that vary by associated task and location [11], [28], [101]. These results suggest that hygiene of surfaces may play an important role in prevention of both occupational and non-occupational exposures from informal e-waste recycling.

2.4.2 Biomarkers

The results for biomarkers for the two occupational groups showed that the mean concentrations for metals were below the BEI reference levels set by the ACGIH [90]. However, the maximum values for Pb exceeded the BEI reference value for urine. Urinary Pb is useful for long-term occupational exposure monitoring as it reflects Pb excreted from blood, bones, and other organs through filtration from the kidney [43]. Studies measuring blood Pb concentrations in other e-waste populations from China, Vietnam, Ghana, and Sweden reported higher levels in workers than our study results in Thailand and Chile [13], [36]-[38], [102].

In addition to the toxic metals Pb and Cd, essential elements were examined in this study. Essential elements are different from toxic elements in that the body relies upon small concentrations for normal metabolic functioning. Serum concentrations of Cu in the Thailand exposure groups were similar to those found in other studies of non-exposed populations (1516 µg/L) [93]. Reference levels for serum Zn were not available. Compared to reference values based on a healthy Canadian population (from the Canadian Health Measures Survey (CHMS)), Thailand's two exposure groups had blood Mn concentrations (15.9 µg/L for the occupational exposure group and 13.8 µg/L for the community exposure group) within the reference range of 14-16 µg/L, while Chile was below this value (6.9 µg/L) [92]. Blood Fe reference values were not found in the literature. Urinary Cu, Ni, and Zn concentrations were near or below the reference values in the Canadian population.

Though mean concentrations of biomarkers were near reference ranges for essential elements and below limits for toxic elements, there is evidence that occupational exposures in Thailand to metals from e-waste are higher than those in Chile and in the non-occupational group based on biomarker concentrations. Although several biomarkers in the Thai community group were higher than those in the Chile occupational group, including blood Mn, and urinary Fe, Pb, Ni, Cu and Zn, more studies are needed to determine if this difference is due to home and community exposures to e-waste or from other factors, including diet or background levels in the environment. Overall, we found that levels of some toxic metals in biomarkers were approaching levels of concern, while essential metals were found to be within or below reference ranges.

2.4.3 Regression models

The regressions performed using demographic variables as predictors indicated that some variation within the individual exposure groups of some of the biomarkers could be explained by sex, age, income, BMI, and education. However, for several biomarkers we did not see any significant explanatory variables correlated with the biomarker of interest, nor did any of the demographic variables alone explain all observed variability. This suggests that there are other explanations for the variations in concentrations of different biomarkers; personal genetics, diet, and behavior may explain part of the observed variation.

2.4.4 Routes of exposure

A common observation amongst informal e-waste workers is a lack of exposure controls, personal protective equipment (PPE), and training to reduce or prevent exposures [67], [103], [104]. This increases the likelihood of occupational exposures to metals. In addition, environmental contamination seen in informal e-waste settings may expose workers and community members alike [103], [105]-[107]. Elevated concentrations of Pb were found in rice, soil, water, environmental air samples, and surface wipe samples from Thailand. We also saw the highest levels of blood lead in the Thailand occupational exposure group for both blood and urine biomarkers. This finding is consistent with other studies that have examined non-occupationally exposed populations near e-waste sites in Ghana and China. Concentrations of metal biomarkers for these non-exposed groups were similar to the concentrations of workers themselves [36], [102], [108], [109]. The higher concentrations found in workers in Thailand compared to Chile may be accounted for by differences in industrial hygiene practices. The highest maximum concentrations in work surface wipe samples were found in Chile, but the biomarker concentrations were higher in the Thai occupational group with the sole exception of Cd. This finding elucidates an important opportunity for intervention to protect worker and community health near e-waste sites. Potential routes of exposure for different metals as determined by this study are shown in Figure 2-6.

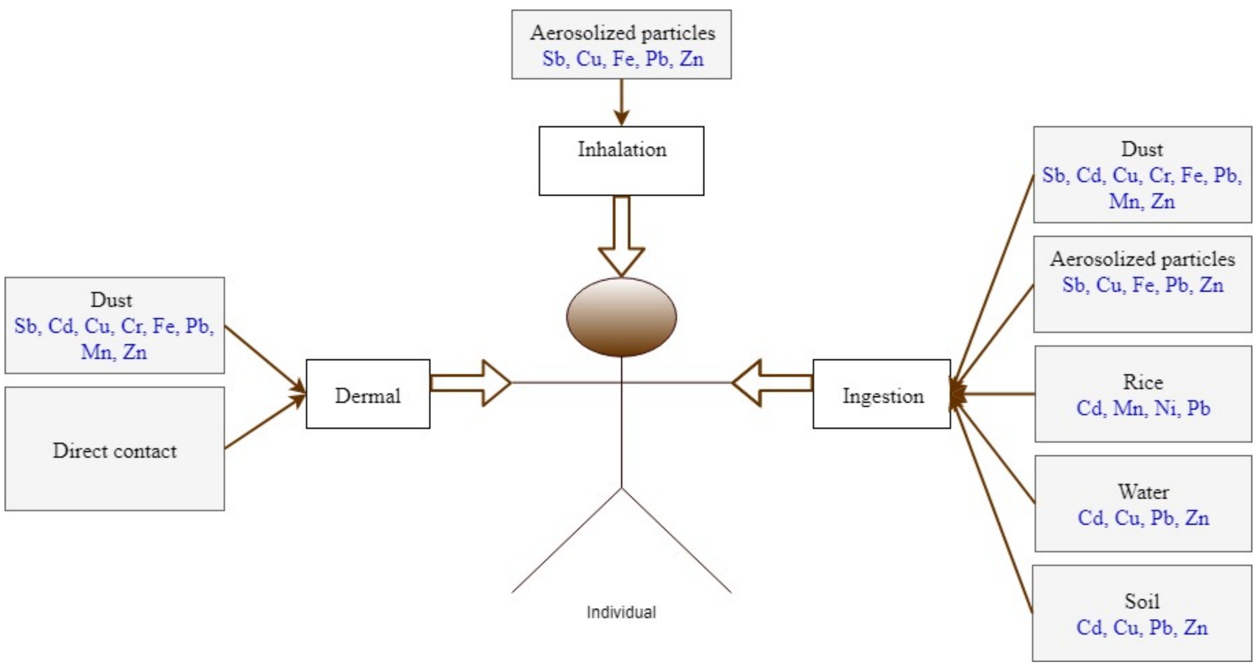


Figure 2-6 Study summary showing the media in which at least one metal was measured and the potential routes of exposure in this study.

2.4.5 Method of Triads

Food surface and work surface wipe samples for both Thai exposure groups tended to be highly correlated, which was not true in the Chile exposure group (data shown in Appendix B, Table B-6). Food and wipe samples from Chile had weaker correlation coefficients in general and also were more likely to have significantly different means than the Thailand samples, as shown, in part, in Figure 2-2. In total, only six of the eleven eligible calculations (Table 2-13) were valid for the method of triads as five validity coefficients were calculated to be greater than one and were therefore Heywood cases. Heywood cases can occur for several reasons, including low sample sizes, which may be likely in this case (see Appendix B, Table B-6 for sample sizes) [95]. Additionally, it is possible that not all area and personal exposures are positively correlated in all cases. Other studies have found that Heywood cases are not uncommon [110]. Of the valid cases, work wipes had the highest validity coefficient for Cu in the community exposure group when compared with the two biomarkers (serum and urine), but food wipe samples had the highest concentration when compared with biomarkers or with either biomarker (serum or urine) and food wipe samples. For Mn samples among the Chile exposure group, work wipe samples had a higher validity coefficient than food wipe or urine samples. Finally, Zn concentrations in samples from the Chile exposure group had the highest validity coefficient in urine when compared with food wipe and area air sampling. Overall, we see that work and food wipes had higher validity for Cu and Mn exposures in Thailand, but that the urinary biomarker for Zn was the most valid measure in Chile. More studies are needed to determine whether wipe samples might be better measurements of exposure in informal recycling that occurs in homes in a setting like Thailand, or if wipe samples are better for certain metals, like Cu and Mn, but not necessarily for all metals, like Zn

2.4.6 Impacts on Public Health

This study provided evidence of environmental contamination from e-waste recycling activities and the need for public health interventions. Elevated metal concentrations were found in samples of rice, soil, and surface water in Thailand. Although surface water is not used for drinking in this community, it is used to water poultry and livestock and to irrigate crops, and therefore presents a risk to humans who consume these agricultural goods. A safe area is needed for the disposal of waste from e-waste recycling. For example, in Thailand, CRTs that are broken and disposed of in the refuse dump contain leaded glass, which can leach into the local environment. Proper community controls to limit and contain e-waste exposures are needed to protect communities in e-waste sites.

The lack of significant differences between work and food surface wipe samples in Thailand and environmental concentrations of metals near the refuse dump, considered together with the biomarker results, suggest that community members in areas where e-waste recycling is prevalent are at risk to exposures to metals. Furthermore, workers in informal settings like those in Thailand are at risk of a double-exposure where they are in contact with e-waste metals not only during work hours, but also in their homes and in the community through environmental pathways.

In future studies or in public health practice, our Method of Triads results can guide sampling decisions for monitoring exposures and health of an e-waste population. This information will be especially useful in settings where the collection and analysis of samples is expensive so that the single best sample type for exposures of concern can be identified and implemented by practitioners. Similarly, knowing which sample type to collect can help researchers to be consistent across studies to accurately assess and compare exposures to e-waste metals over time and space.The extensiveness of the sampling campaign offers valuable information to researchers. The numerous metal types tested for provide information on what metals are important to include in future exposure analyses. The variation of exposure is demonstrated between the three exposure groups, which is valuable for consideration by future researchers who should include the use of a reference and/or control population. Finally, this research demonstrates that concentrations of different metals may vary by sample type, and so failure to find concentrations of a metal in one medium does not necessarily mean those metals are absent from the study site.

2.4.7 Limitations

This study had several important limitations. First, the low number of environmental samples collected may not reflect the true mean concentrations in soil, air, water, and rice, and may also vary seasonally. Next, the biomarkers collected were analyzed at the same certified laboratory; however, the LODs were different for a few metals between the three exposure groups. For example, urinary Cd had a LOD of 1.0 μg/L in the Thai occupational group, which was 250 times higher than the LOD of 0.004 μg/L in the other two groups. This is important to consider as the urinary Cd mean was not calculated for the Thai occupational group due to the high percentage of samples <LOD. Additionally, we did not consider diet in this study, which is likely an important contributor to biomarker concentrations, particularly for metals. Fourth, the study had to use convenience sampling methods for recruitment due to circumstances outside of the control of the study design, including the informal nature of the work and social norms and practices in each country. Therefore, our study population may not be representative of the larger population from any of the exposure groups.

Finally, there were only six valid calculations for use in comparison of exposure measurements in the Method of Triads. The number of participants who had valid air samples was limited, and so we were unable to run Pearson correlations or use them in the method of triads. For example, the number of participants in the community exposure group from Thailand who had viable wipe and area air samples for Fe and Cu was six. This prohibits the inclusion of these variables in the method of triads. However, this also provided useful information about the limitations of using area air samples as markers of exposure for e-waste settings where activities are performed outdoors and through use of hand tools.

2.4.8 Future directions

This study identifies opportunities for future research. A comprehensive study on air concentrations of different metals is needed to better identify the exposure risks associated with inhalation from e-waste recycling. Collection of air samples over a longer time period (or with a higher flowrate) and downwind of the refuse dump during burning events would help determine the extent to which burning of e-waste pollutes the local air. Future studies should collect PBZ samples for at least eight hours to ensure that there is sufficient volume of air collected to determine concentrations. Because the Method of Triads results were limited due to small sample sizes and Heywood Cases, more studies are needed to replicate and increase confidence in our findings. Future studies should also consider the biological interaction of toxic and essential metals. For instance, both Cd and Pb competitively inhibit the uptake of essential metals by the body [111], [112]. Finally, for all environmental sample types, further studies are needed to determine that the elevated metal concentrations are from e-waste recycling and not from a different source, or from non-anthropogenic processes.

2.5 Conclusions

Elevated concentrations of Pb were found in soil, surface water, rice, and dust samples from Thailand, and in surface dust samples from Chile, suggesting multiple routes of exposure to Pb for occupational and non-occupational populations exposed to e-waste recycling activities. Biomarker concentrations were highest among Thai e-waste recyclers, and this group is likely at risk of both occupational and non-occupational exposures to metals from e-waste. Despite higher concentrations in surface wipe samples in Chile, the workers had lower concentrations of blood and urine biomarkers, which may be due to better hygiene practices, including separation of work and food areas. Results from the method of triads analysis suggest that work and food wipe samples had the highest validity for at least one metal in Thailand, while urine samples had the highest validity for measuring exposure to Zn in Chile. More studies are needed to determine under what conditions biomarkers have greater validity as a measure of exposure than wipe samples.

2.6 Bibliography

1. Zhang, T. et al. Heavy metals in human urine, foods and drinking water from an e-waste dismantling area: Identification of exposure sources and metal-induced health risk. Ecotoxicol. Environ. Saf. 169, 707–713 (2019).
2. Fujimori, T. et al. Impact of metals in surface matrices from formal and informal electronic-waste recycling around Metro Manila, the Philippines, and intra-Asian comparison. J. Hazard. Mater. 221–222, 139–146 (2012).
3. Leung, A. O. W., Duzgoren-Aydin, N. S., Cheung, K. C. & Wong, M. H. Heavy metals concentrations of surface dust from e-waste recycling and its human health implications in southeast China. Environ. Sci. Technol. 42, 2674–2680 (2008).
4. Pradhan, J. K. & Kumar, S. Informal e-waste recycling: Environmental risk assessment of heavy metal contamination in Mandoli industrial area, Delhi, India. Environ. Sci. Pollut. Res. 21, 7913–7928 (2014).
5. Quan, S. X. et al. Spatial distribution of heavy metal contamination in soils near a primitive e-waste recycling site. Environ. Sci. Pollut. Res. Int. 22, 1290–1298 (2015).

6. Fujimori, T. & Takigami, H. Pollution distribution of heavy metals in surface soil at an informal electronic-waste recycling site. Environ. Geochem. Health 36, 159–168 (2014).

7. Awasthi, A. K., Wang, M., Awasthi, M. K. & Wang, Zhishi, Li, J. Environmental pollution and human body burden from improper recycling of e-waste in China: A short-review. Environ. Pollut. 243, 1310–1316 (2018).

8. Grant, K. et al. Health consequences of exposure to e-waste: a systematic review. Lancet. Glob. Heal. 1, e350-61 (2013).

9. Huang, C. L. et al. Potential health risk for residents around a typical e-waste recycling zone via inhalation of size-fractionated particle-bound heavy metals. J. Hazard. Mater. 317, 449–456 (2016).

10. Yekeen, T. A. et al. Assessment of health risk of trace metal pollution in surface soil and road dust from e-waste recycling area in China. Environ. Sci. Pollut. Res. 23, 17511–17524 (2016).

11. Lau, W. K. Y., Liange, P., Man, Y. B., Chung, S. S. & Wong, M. H. Human health risk assessment based on trace metals in suspended air particulates, surface dust, and floor dust from e-waste recycling workshops in Hong Kong, China. Environ. Sci. Pollut. Res. 21, 3813–3825 (2014).

12. Wu, Y. et al. Tetrabromobisphenol A and heavy metal exposure via dust ingestion in an e-waste recycling region in Southeast China. Sci. Total Environ. 541, 356–364 (2016).

13. Julander, A. et al. Formal recycling of e-waste leads to increased exposure to toxic metals: an occupational exposure study from Sweden. Environ. Int. 73, 243–51 (2014).

14. Ceballos, D. M. & Dong, Z. The formal electronic recycling industry: Challenges and opportunities in occupational and environmental health research. Environ. Int. 95, 157–166 (2016).

15. Larese, F., Gianpietro, A., Venier, M., Maina, G. & Renzi, N. In vitro percutaneous absorption of metal compounds. Toxicol. Lett. 170, 49–56 (2007).

16. ATSDR. Toxic Guide for Lead. (2007).

17. Sthiannopkao, S. & Wong, M. H. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Sci. Total Environ. 463–464, 1147–1153 (2013).

18. Cui, J., Luo, C., Tang, C. W., Chan, T. & Li, X. Speciation and leaching of trace metal contaminants from e-waste contaminated soils. J. Hazard. Mater. 329, 150–158 (2017).

19. Duruibe, J. O., Ogwuegbu, M. O. C. & Egwurugwu, J. N. Heavy metal pollution and human biotoxic effects. Int. J. Phys. Sci. 2, 112–118 (2007).

20. Su, C., Jiang, L. & Zhang, W. A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. Environ. Skept. Critics 3, 24–38 (2014).

21. Luo, C. et al. Heavy metal contamination in soils and vegetables near an e-waste processing site, south China. J. Hazard. Mater. 186, 481–490 (2011).

22. Wu, C., Luo, Y., Deng, S., Teng, Y. & Song, J. Spatial characteristics of cadmium in topsoils in a typical e-waste recycling area in southeast China and its potential threat to shallow groundwater. Sci. Total Environ. 472, 556–561 (2014).

23. Tang, X. et al. Heavy metal and persistent organic compound contamination in soil from Wenling: An emerging e-waste recycling city in Taizhou area, China. J. Hazard. Mater. 173, 653–660 (2010).

24. Coby S.C., W., S.C., W., Nurdan S., D.-A., Adnan, A. & Ming H., W. Trace metal contamination of sediments in an e-waste processing village in China. Environ. Pollut. 145, 434–442 (2007).

25. Wong, C. S. C., Duzgoren-Aydin, N. S., Aydin, A. & Wong, M. H. Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. Environ. Pollut. 148, 62–72 (2007).

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

27. Zhao, G. F., Zhou, H. D. & Wang, Z. J. Concentrations of selected heavy metals in food from four e-waste disassembly localities and daily intake by local residents. J. Environ. Sci. Heal. Part A   Toxic/Hazardous Subst. Environ. Eng. 45, 824–835 (2010).

28. Zheng, J. et al. Heavy metals in food, house dust, and water from an e-waste recycling area in South China and the potential risk to human health. Ecotoxicol. Environ. Saf. 96, 205–212 (2013).

29. Simmons, R. W., Pongsakul, P., Saiyasitpanich, D. & Klinphoklap, S. Elevated levels of ladmium and zinc in paddy soils and elevated levels of cadmium in rice grain downstream of a zinc mineralized area in Thailand: Implications for public health. Environ. Geochem. Health 27, 501–511 (2005).

30. Phaenark, C., Pokethitiyook, P., Kruatrachue, M. & Ngernsansaruay, C. Cd AND Zn ACCUMULATION IN PLANTS FROM THE PADAENG ZINC MINE AREA. Int. J. Phytoremediation 11, 479–495 (2009).

31. Wu, Q. et al. Heavy metal contamination of soil and water in the vicinity of an abandoned e-waste recycling site: Implications for dissemination of heavy metals. Sci. Total Environ. 506–507, 217–225 (2015).

32. Wittsiepe, J. et al. Pilot study on the internal exposure to heavy metals of informal-level electronic waste workers in Agbogbloshie, Accra, Ghana. Environ. Sci. Pollut. Res. 1–11 (2016). doi:10.1007/s11356-016-8002-5

33. Tucker, P. G. et al. ATSDR Cadmium Toxicity. 1–63 (2011).

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

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

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

37. Li, K. Q. et al. Genotoxic effects and serum abnormalities in residents of regions proximal to e-waste disposal facilities in Jinghai, China. Ecotoxicol. Environ. Saf. 105, 51–58 (2014).

38. Noguchi, T. et al. Exposure assessment of lead to workers and children in the battery recycling craft village, Dong Mai, Vietnam. J. Mater. Cycles Waste Manag. 16, 46–51 (2014).

39. Ni, W. et al. Hair mercury concentrations and associated factors in an electronic waste recycling area, Guiyu, China. Environ. Res. 128, 84–91 (2014).

40. Schecter, A. et al. Biomonitoring of metals, polybrominated diphenyl ethers, polychlorinated biphenyls, persistent pesticides in Vietnamese female electronic waste recyclers. J. Occup. Environ. Med. 60, (2017).

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

42. Luque-Garcia, J. L. & Neubert, T. A. Sample preparation for serum/plasma profiling and biomarker identification by mass spectrometry. J. Chromatogr. A 1153, 259–276 (2007).

43. Barbosa, F., Tanus-Santos, J. E., Gerlach, R. F. & Parsons, P. J. A Critical Review of Biomarkers Used for Monitoring Human Exposure to Lead: Advantages, Limitations, and Future Needs. Environ. Health Perspect. 113, 1669–1674 (2005).

44. Lucchini, R. G., Aschner, M., Kim, Y. & Saric, M. Manganese. in Handbook on the Toxicology of Metals: Fourth Edition 1, 975–1011 (Elsevier, 2014).

45. Ellingsen, D. G., Moller, L. B. & Aaseth, J. Copper. in Handbook on the Toxicology of Metals: Fourth Edition (eds. Nordberg, G. F., Fowler, B. A. & Nordberg, M.) 425–427 (Academic Press, 2015). doi:10.1016/B978-0-12-811410-0.00026-X

46. Nordberg, G. F. Biomarkers of exposure, effects and susceptibility in humans and their application in studies of interactions among metals in China. Toxicol. Lett. 192, 45–49 (2010).

47. Aylward, L. L. et al. Sources of Variability in Biomarker Concentrations. J. Toxicol. Environ. Heal. - Part B Crit. Rev. 17, 45–61 (2014).

48. Hoet, P., Deumer, G., Bernard, A., Lison, D. & Haufroid, V. Urinary trace element concentrations in environmental settings: Is there a value for systematic creatinine adjustment or do we introduce a bias? J. Expo. Sci. Environ. Epidemiol. 26, 296–302 (2016).

49. Pereira, T. S. S., Cade, N. V., Mill, J. G., Sichieri, R. & Molina, M. D. C. B. Use of the method of triads in the validation of sodium and potassium intake in the Brazilian longitudinal study of adult health (ELSA-Brasil). PLoS One 11, 1–10 (2016).

50. Bhakta, D. et al. A semiquantitative food frequency questionnaire is a valid indicator of the usual intake of phytoestrogens by south Asian women in the UK relative to multiple 24-h dietary recalls and multiple plasma samples. J Nutr 135, 116–23 (2005).

51. Verkleij-Hagoort, A. C. et al. Validation of the assessment of folate and vitamin B12 intake in women of reproductive age: The method of triads. European Journal of Clinical Nutrition 61, (2007).

52. Zekovic, M. et al. Validity of the food frequency questionnaire assessing the folate intake in women of reproductive age living in a country without food fortification: Application of the method of triads. Nutrients 9, (2017).

53. Weir, R. R. et al. Validation of a food frequency questionnaire to determine vitamin D intakes using the method of triads. J. Hum. Nutr. Diet. 29, 255–261 (2016).

54. Djekic-Ivankovic, M. et al. Validity of an FFQ assessing the Vitamin D intake of young Serbian women living in a region without food fortification: the method of triads model. Public Health Nutr. 19, 437–445 (2014).

55. Burkholder-Cooley, N. M. et al. Validating polyphenol intake estimates from a food-frequency questionnaire by using repeated 24-h dietary recalls and a unique method-of-triads approach with 2 biomarkers. Am. J. Clin. Nutr. 105, 685–694 (2017).

56. Krogholm, K. S. et al. Evaluation of flavonoids and enterolactone in overnight urine as intake biomarkers of fruits, vegetables and beverages in the Inter99 cohort study using the method of triads. Br. J. Nutr. 108, 1904–1912 (2012).

57. Andersen, L. F. et al. Evaluation of three dietary assessment methods and serum biomarkers as measures of fruit and vegetable intake, using the method of triads. Br. J. Nutr. 93, 519 (2005).

58. Neitzel, R., Andersson, M. & Andersson, E. Comparison of multiple measures of noise exposure in paper mills. Ann. Occup. Hyg. 60, 581–596 (2016).

59. Chavarro, J. E. et al. Validity of Self-Assessed Sexual Maturation Against Physician Assessments and Hormone Levels. J. Pediatr. 186, 172–178.e3 (2017).

60. Rees-Punia, E. et al. Demographic-specific Validity of the Cancer Prevention Study-3 Sedentary Time Survey. Med. Sci. Sport. Exerc. 1 (2018). doi:10.1249/MSS.0000000000001743

61. Dixon, D. & Johnston, M. Cognitive representations of disability behaviours in people with mobility limitations: Consistency with theoretical constructs. Disabil. Rehabil. 30, 126–133 (2008).

62. Ockã, C. & Kaaks, R. J. Biochemical markers as additional measurements in dietary validity studies: application of the method of triads with examples from the European Prospective Investigation into Cancer and Nutrition13. Am. J. Clin. Nutr. 65, 1240–1245 (1997).

63. White, E. Design and interpretation of studies of differential exposure measurement error. Am. J. Epidemiol. 157, 380–387 (2003).

64. Thailand Ministry of Labour. New Minimum Wage Rate Table. National Wage Committee’s Notification on Minimum Wage Rate (No.8) (2010). Available at: http://www.mol.go.th/en/employee/interesting_information/6319. (Accessed: 16th October 2018)

65. Simmons, K., Deatric, J., Levis, B. SESD Operating Procedure: Soil Sampling. (2014). doi:SESDPROC-300-R3

66. Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M. & Böni, H. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25, 436–458 (2005).

67. Robinson, B. H. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–91 (2009).

68. Central Laboratory Thailand Company Limited. Available at: https://www.centrallabthai.com/index.php/en/about-us/cer. (Accessed: 12th January 2018)

69. Elledge, M. et al. Working document for information and use in discussions related to contaminants and toxins in the GSCTFF. Fifth Sess, (2011).

70. Fao, J. et al. Codex Alimentarius Commission. (2017).

71. Codex Alimentariu. General standard for contaminants and toxins in food and feed. (2018).

72. Herrman, J. L. & Younes, M. Background to the ADI / TDI / PTWI. Regul. Toxicol. Phamarcology 113, 109–113 (1999).

73. FAO/WHO. Joint FAO/WHO expert committee on food additives. Sixty-first meeting. Summary and conclusions. (2003).

74. Food and Nutrition Board, Institute of Medicine, N. A. Dietary Reference Intakes (DRIs): Recommended Dietary Allowances and Adequate Intakes , Vitamins Food and Nutrition Board , Institute of Medicine , National Academies. (1997). doi:10.1111/j.1753-4887.2004.tb00011.x

75. La-Up, A., Wiwatanadate, P., Pruenglampoo, S. & Uthaikhup, S. Recommended rice intake levels based on average daily dose and urinary excretion of cadmium in a cadmium-contaminated area of northwestern Thailand. Toxicol. Res. 33, 291–297 (2017).

76. United States Environmental Protection Agency. Surface water sampling, SESDPROC-201-R3. (2013). doi:10.1021/np100470h

77. American Public Health Association, American Water Works Association & Water Environment Federation. Standard methods for the examination of water and wastewater. (2017).

78. United States Environmental Protection Agency. Drinking water requirements for states and public water systems: Lead and Copper Rule (2018). Available at: https://www.epa.gov/dwreginfo/lead-and-copper-rule. (Accessed: 20th December 2018)

79. Occupational Safety and Health Administration. Surface contaminants, skin exposure, biological monitoring and other analyses. in OSHHA Technical Manual (United States Department of Labor, OSHA, 2014).

80. Septon, J., Abel, R. & Simmons, M. Metal and Metalloid Particulates in Workplace Atmosphere (ICP Analysis). 1–43 (2002).

81. Lau, W. K. Y., Liang, P., Man, Y. B., Chung, S. S. & Wong, M. H. Human health risk assessment based on trace metals in suspended air particulates, surface dust, and floor

dust from e-waste recycling workshops in Hong Kong, China. Environ. Sci. Pollut. Res. Int. 21, 3813–25 (2014).

82. Palmer, C. D., Lewis, M. E., Geraghty, C. M., Barbosa, F. & Parsons, P. J. Determination of lead, cadmium and mercury in blood for assessment of environmental exposure: A comparison between inductively coupled plasma-mass spectrometry and atomic absorption spectrometry. Spectrochim. Acta - Part B At. Spectrosc. 61, 980–990 (2006).

83. Nixon, D. E. & Moyer, T. P. Routine clinical determination of lead, arsenic, cadmium, and thallium in urine and whole blood by inductively coupled plasma mass spectrometry. Spectrochim. Acta - Part B At. Spectrosc. 51, 13–25 (1996).

84. Hornung, R. W. & Reed, L. D. Estimation of average concentration in the presence of nontedetectable values. Appl. Occup. Environ. Hyg. 5, 46–541 (1990).

85. White, E. Measurement error in biomarkers: sources, assessment, and impact on studies. in IARC scientific publications (ed. Hartemink, Alfred E., McBratney, Alex, Minasny, B.) 63, 76A–83A (2008).

86. Department of Soil Protection & Netherlands. The Netherlands soil contamination guidelines, Netherlands intervention values for soil remediation, reference #DBO/07494013. (1994).

87. Zarcinas, B. A., Pongsakul, P., Mclaughlin, M. J. & Cozens, G. Heavy metals in soils and crops in southeast Asia. 2. Thailand. Environ. Geochem. Health 26, 359–371 (2004).

88. Obiri, S., Ansa-Asare, O. D., Mohammed, S., Darko, H. F. & Dartey, A. G. Exposure to toxicants in soil and bottom ash deposits in Agbogbloshie, Ghana: human health risk assessment. Environ. Monit. Assess. 188, (2016).

89. EPA. Aquatic Life Ambient Water Quality Criteria Update for Cadmium - 2016. 304, (2016).

90. ACGIH. TLVs and BEIs: Threshold limit values for chemical substances and physical agents and biological exposure indices. (American Conference of Governmental Industrial Hygienists, 2017).

91. Shim, Y. K., Lewin, M. D., Ruiz, P., Eichner, J. E. & Mumtaz, M. M. Prevalence and associated demographic characteristics of exposure to multiple metals and their species in human populations: the United States NHANES, 2007-2012. J. Toxicol. Environ. Heal. Part A 80, 502–512 (2017).

92. Saravanabhavan, G. et al. Human biomonitoring reference values for metals and trace elements in blood and urine derived from the Canadian Health Measures Survey 2007–2013. Int. J. Hyg. Environ. Health 220, 189–200 (2017).

93. ATSDR. Public health statement - copper. doi:http://dx.doi.org/10.1155/2013/286524

94. CDC & NIOSH. Adult Blood Lead Epidemiology & Surveillance (ABLES). About ABLES (2018). Available at: https://www.cdc.gov/niosh/topics/ABLES/description.html. (Accessed: 18th May 2018)

95. Guttman, L. Some necessary conditions for common-factor analysis. Psychometrika 19, 149–161 (1954).

96. Sebastian, A. & Prasad, M. N. V. Cadmium minimization in rice. A review. Agron. Sustain. Dev. 34, 155–173 (2014).

97. Fu, J. et al. High levels of heavy metals in rice (Oryza sativa L.) from a typical E-waste recycling area in southeast China and its potential risk to human health. Chemosphere 71, 1269–1275 (2008).

98. Bi, X., Li, Z., Zhuang, X., Han, Z. & Yang, W. High levels of antimony in dust from e-waste recycling in southeastern China. Sci. Total Environ. 409, 5126–5128 (2011).

99. Adgate, J. L. et al. Relationships between personal, indoor, and outdoor exposures to trace elements in PM2.5. Sci. Total Environ. 386, 21–32 (2007).

100. Harrison, R. M. et al. Personal exposure monitoring of particulate matter, nitrogen dioxide, and carbon monoxide, including susceptible groups. Occup. Environ. Med. 59, 671–679 (2002).

101. Wang, J. et al. Heavy metal pollution in the surface dust from e-waste disposal place and its ecological risk assessment. in Advanced Materials Research 347–353, 2360–2364 (2012).

102. Wang, H., Lv, S., Li, F., Liu, Q. & Ke, S. Study on the changes of urinary 8-hydroxydeoxyguanosine levels and burden of heavy metal around e-waste dismantling site. Sci. Total Environ. 408, 6092–6099 (2010).

103. Heacock, M. et al. E-Waste and Harm to Vulnerable Populations: A Growing Global Problem. Environ. Health Perspect. 550, 550–555 (2015).

104. Perkins, D. N., Brune Drisse, M.-N., Nxele, T. & Sly, P. D. E-waste: a global hazard. Ann. Glob. Heal. 80, 286–95 (2014).

105. Ackah, M. Informal e-waste recycling in developing countries: review of metal(loid)s pollution, environmental impacts and transport pathways. Environ. Sci. Pollut. Res. 24, 24092–24101 (2017).

106. Zeng, X., Xu, X., Boezen, H. M. & Huo, X. Children with health impairments by heavy metals in an e-waste recycling area. Chemosphere 148, 408–15 (2016).

107. Tang, J., Huang, Z. & Pan, X. D. Exposure assessment of heavy metals (Cd, Hg, and Pb) by the intake of local foods from Zhejiang, China. Environ. Geochem. Health 36, 765–771 (2014).

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

109. Tokumaru, T., Ozaki, H., Onwona-Agyeman, S., Ofosu-Anim, J. & Watanabe, I. Determination of the Extent of Trace Metals Pollution in Soils, Sediments and Human Hair at e-Waste Recycling Site in Ghana. Arch. Environ. Contam. Toxicol. 73, 377–390 (2017).

110. Ocka, C., Kaaks, R. Biochemical markers as additional measurements in dietary validity studies: Application of the Method of Triads with examples from the European Prospective Investigation into Cancer and Nutrition. Am. J. Clinical Nutr 65, 1240-1245 (1997).

111. Prozialeck, W. C., Lamar, P. C. & Edwards, J. R. Effects of sub-chronic Cd exposure on levels of copper, selenium, zinc, iron and other essential metals in rat renal cortex. Toxicol. Reports 3, 740–746 (2016).

112. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K. & Sutton, D. J. Molecular, Clinical and Env. Toxy. EXS 100, 365–396 (2010).

Chapter 3 : Occupational Noise Exposure and Injuries Among E-waste Workers in Thailand and Chile

Chapter 3 Abstract

Background: Informal e-waste recycling workers use crude methods to disassemble and recovery valuable materials from waste electronics. Poor access to personal protective equipment and regulated work space potentially exposes workers to hazards, including loud noise and conditions that might cause injuries. There is a lack of quantitative studies examining the physical hazards associated with e-waste work in informal settings.

Methods: Surveys were collected from e-waste workers in Thailand and Chile. Data from the surveys included demographic information, noise exposures, work tasks, occupational injuries, and information about the worst injury over the previous six months. Hearing tests were administered to participants and personal noise exposures were measured during a work shift. In addition, video footage was collected of workers performing routine work tasks and enumerated using a tool designed to quantify the frequency of tool use, tasks, ergonomic stressors, and use of personal protective equipment. Regression models were developed to determine the odds of injury (logistic regression) and the incidence rate ratio of injury (Poisson regression) based on the frequency of different work attributes for both the survey and video data sets.

Results: The mean time-weighted average occupational noise exposure was below the recommended limit of 85 dBA for all workers. Evidence of noise induced hearing loss was found

in the audiograms from both countries, with the highest prevalence of mild or worse hearing loss found in Thailand. In both countries, 60% of workers were injured at least once in the previous six months. Of those injured, 43% in Thailand and 66% in Chile were injured more than once during the same time period. From the video analysis, we found a high frequency of ergonomic stressors and working near sharp metals in both countries. Odds of injury occurrence in Thailand were predicted to increase based on increased frequencies of work noise and to decrease with regular use of PPE. In Chile, odds of injury were predicted to increase with report of having a work task that results in more frequent injury and decreases with report of frequently buying or selling of e-waste as a work task. In Thailand, the incidence rate ratio of injury was reported to increase with younger age groups, lower levels of education, more frequent use of pliers/scissors, and working near sharp metal. In Chile, the injury incidence rate ratio increased with older age groups, higher education, report of a task frequently resulting in injury, use of cotton gloves, repetitive arm motion, and frequent lifting of <20 pounds; the incidence rate ratio decreased with more frequent work noise and more frequently engaging in buying/selling of e-waste materials.

Conclusion: Time-weighted average noise exposures of e-waste workers were below the level associated with noise induced hearing loss, but self-reported perceived noise was associated with injury in Thailand. Evidence of NIHL was present in majority of the workers despite the lower levels of noise exposure measured. This study found a high incidence of injury among informal e-waste workers. A variety of predictors were found to be significant in the models estimating the odds or incidence of injury, including demographic variables, tasks, perceived noise levels, PPE use, tools, and product type.

3.1 Introduction

3.1.1 Introduction to occupational safety in global settings

Inadequate workplace health and safety practices are estimated to cost 3.94% of global Gross Domestic Product each year in the formal sector [1]. Occupational injuries can be disabling or fatal, producing a considerable negative health and economic impact on workers who experience them. Comprehensive hazard identification and risk assessment activities can provide information that facilitates prevention of injuries in the work place, as well as development of training programs for workers [2]. Prevention of injuries is one of the goals identified in the National Institute for Occupational Safety and Health (NIOSH)'s Total Worker Health (TWH) framework [3].

There may be a greater number of injuries in the informal sector than is reflected in current estimations of workplace injury prevalence in the formal sector; however, there are few data available on this sector, making accurate estimation difficult [4]-[6]. Workers in developing countries and the informal sector are considered to be at a greater risk to injury due to minimal legal regulation and enforcement, and the rarity or absence of occupational health and safety programs [7]. Occupational health and safety services cover only 5% to 10% of the population of the developing world, and the rate of occupational injury and illness in these countries is expected to double by 2025 [8]. Impacts of injuries experienced by workers in the informal sector, particularly in developing countries, may be larger than those in other industries as informal workers typically lack access to health care and social safety nets, including workers compensation [9], [10].

Informal electronic waste recycling is a growing industry around the globe, as the amount of discarded electronics, “e-waste”, grows each year [11]. E-waste is comprised of electronic products, parts, and equipment that has reached the end of its useable life. Despite a ban under the United Nations Basel Convention on Hazardous Waste, e-waste is shipped from high- and middle- income countries to middle- and low-income countries where it is recycled by rudimentary methods to recover valuable materials [12]-[14]. Although e-waste recycling provides a valuable source of income, it contains many hazardous materials, and is expensive to recycle in a formal manner that protects the health of workers, communities, and the environment [15]-[17]. E-waste workers in the informal sector are largely from lower socioeconomic and marginalized populations [17], [18]. Globalization has resulted in a trend of shifting of the highest risk jobs, including e-waste recycling, to developing countries, and has created a greater need for improved standards in new and emerging informal occupational settings [9], [19].

3.1.2 Noise exposure, health outcomes, and injury risk

Workers are at risk of noise induced hearing loss (NIHL) from occupational sources of noise. In 2005, it was estimated that, globally, 16% of disabling hearing loss was due to workplace noise exposure, with higher rates of NIHL in developing countries [20]. E-waste workers exposed to possible ototoxins (e.g., heavy metals) in addition to noise potentially have a further increased risk for hearing loss [21]. NIOSH has a recommended exposure limit (REL) for noise to protect against NIHL of 85 A-weighted decibels (dBA) expressed as an 8-hour Time-Weighted Average (TWA) [22]. However, this limit does not provide protection for non-auditory effects of noise exposure [23], [24]. In addition to NIHL, noise exposure is associated with other negative health outcomes, including hypertension, ischemic heart disease, stress, sleep disturbance, performance, and psychosocial impacts [25].

Noise exposures at work have also been shown to increase injury risk [26], [27]. Occupational noise exposure has been linked to an increase in injury in different types of formal industry jobs [28]-[30]. However, this association has not been tested among informal workers. Several studies show that among occupational groups exposed to noise there is a further increase in risk of work-related injury among workers who suffered from NIHL [31]-[33]. Workers with compromised hearing may miss verbal cues or other hearing-critical environmental stimulus that would alert them to danger, increasing risk of injury.

3.1.3 Hazards and injuries in e-waste

Informal e-waste workers engage in multiple tasks throughout the process of recycling of electronic equipment. The first step in the process is the collection of e-waste or components. In some locations, for example Thailand, workers reported travelling to nearby larger cities to purchase and collect e-waste material in a pickup truck. In other locations, for example Chile, waste electronics were collected by individuals on motor taxis using the municipal system of placing recyclables by the curb or exchanged at markets. After materials are collected, they are sorted by type and sold or distributed to workers for further processing.

The next step in the process is the manual disassembly of electronics into raw materials or components such as printed circuit boards. The process of manual disassembly largely depends on the type of electronic being recycled. For example, one of the first steps in manual disassembly of cathode ray tube (CRT) monitors is to break the glass, either with a hammer or by dropping the monitor from a height. For other types of electronics, basic hand tools and power tools are often used by workers to separate components. The last step in the process is to again sort the materials and components after disassembly, and then to sell the recovered materials.

Workers engaged in e-waste recycling are directly exposed to a variety of occupational health hazards, including metals, physical hazards (e.g. noise and musculoskeletal issues), and injuries [13], [34]. Several studies have described physical hazards of e-waste, including the use of primitive or inappropriate tools, lack of personal protective equipment (PPE), and burning of e-waste to recover materials [13], [17], [35]-[38]. A study of e-waste recyclers in Agbogbloshie, Ghana reported unhygienic working conditions, no use of personal protective equipment, long working hours and little to no job training [38]. Studies on informal recyclers report low worker knowledge of health hazards associated with e-waste recycling [39]-[41]. One of the few studies to report on occupational injuries in e-waste recycling found a high prevalence of injuries among e-waste recyclers, and a low utilization of PPE [42]. Of the limited studies published on noise exposures and NIHL among e-waste workers, one study reported that 40% of workers were exposed to levels above the NIOSH 85 dBA REL, and that complaints of hearing loss were common [36]. Although the body of scientific literature focused on informal e-waste recycling is rapidly expanding, there is a paucity of information on which tasks, tools, PPE and e-waste products recycled are more likely to result in injury. Additionally, the association between noise exposure and injury rates among e-waste workers has not been explored.

3.1.4 Research Objectives

The overall objective of this study was to determine which aspects of informal e-waste recycling present the greatest likelihood and rate of injury. In order to accomplish this, three specific aims were developed. The first was to determine the extent of noise exposure and subsequent NIHL of e-waste workers in informal settings in Thailand and Chile. The second aim was to examine the occurrence of injuries amongst e-waste workers in each country, and to estimate the likelihood of injury through examination of job tasks, tool use, PPE, and other characteristics of the job. The third aim was to determine the frequency of injuries amongst e-waste workers based on these same job characteristics.

3.2 Methods

3.2.1 Study sites

Data for this study were collected during 2016-2017 in Thailand and during 2017 in Chile. The research site in Thailand was a rural, agricultural community in the northeastern part of the country. E-waste recycling in this community often occurs inside of homes and workers are either self-employed and work with family or are employed at minimum wage by a member of the community. Some e-waste activities, including the burning of e-waste and dismantling of cathode ray tube (CRT) television screens, occur in the community dump site, which is an unlined, walled-off area in the middle of a rice paddy that the community uses as a landfill. No data collection occurred in the dump site. Some workers in the Thai research site reported only working with e-waste when they were not planting or harvesting crops, while other workers conducted both work activities in parallel.

In Chile, three study sites were selected: the urban towns of Chillan and Temuco and capital city of Santiago. E-waste recyclers in Chile are more likely to work in a designated work space away from the home than in Thailand, although in-home recycling does occur. Additionally, informal e-waste recycling in Chile appears to typically be a primary job, unlike in Thailand. In both Thailand and in Chile, researchers and students from the University of

Michigan partnered with researchers and students from local universities, as well as local governmental bodies, healthcare professionals, and community members.

3.2.2 Human subjects

This study was approved by the Institutional Review Board of the University of Michigan (HUM0014562) in the United States, Mae Fah Luang University (MFU) in Thailand (REH-59104), and the University of Chile – Santiago (Archive Project Nº 101-2017; Act Nº 45). Informed consent was obtained from all subjects prior to participation in any study procedures. Participants were selected in each country using convenience sampling as random sampling was not feasible and was deemed culturally inappropriate by our in-country collaborators.

3.2.3 Survey

In both Thailand and in Chile, surveys were administered by students and community members who were native speakers in each country. Information was collected on personal demographics, hearing, noise, work history, current work tasks, and injury history (Appendix A). Workers in each country were asked about the tasks that they perceived to put them at greatest risk of injury, as well as how often they engaged in certain work behaviors, including wearing PPE, handling different tools and materials, and performing certain job tasks. Workers were asked if they had been injured in the last 6 months; those who had were asked a series of follow-up questions about the *worst* injury received during that time period. After the survey was completed in Thailand, the Chilean survey was revised to ask for more detail, including questions on the length of time working with e-waste (years), the specific tasks performed, questions about which task(s) participants are the most familiar with, and whether or not there are tasks that more frequently result in injury. Therefore, some variables that were available from Chile are not available from Thailand.

3.2.4 Noise exposure and hearing ability

Participants answered questions regarding their hearing ability, including whether they had been diagnosed by a medical professional as having hearing loss, if and for how long they had experienced trouble hearing, whether they work in a noisy environment, and if they had ever experienced a temporary change in their hearing such as muffled sounds or ringing following noise exposure. This latter question was intended to identify the occurrence of a potential temporary change in auditory thresholds, or temporary threshold shift (TTS). Noise exposures were measured over the course of an entire work shift (nominally 8 hours) using a doseBadge (Cirrus Research PLC, Hunmanby, North Yorkshire, United Kingdom) personal noise dosimeter attached to the shirt of participants near the ear. Dosimeters were calibrated immediately before use and were configured to measure a TWA exposure level according to the NIOSH REL: 85 dBA criterion level, 8-hour criterion duration, 80 dBA threshold level, and 3 dBA exchange rate.

Finally, participants were administered a pure-tone audiometric test in a quiet environment by a technician certified by the Council for Accreditation in Occupational Hearing Conservation using an Earscan 3 audiometer and Earscan 3 TDH-39 circumaural headphones. Seven frequencies were tested: 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hertz (Hz).

3.2.5 Video data

In addition to survey data, video footage of participants performing routine e-waste recycling tasks was captured in each country. The video footage was edited to only include segments where the participant was actively working in the camera frame. Ten two-minute segments from the edited footage for each participant was then sampled at equal intervals depending on the total footage time available per participant. The activities, tasks, tools used, electronic products being recycled, as well as various health and safety issues, were summarized using a tool developed for this study (see Appendix C, table C-1). The tasks performed and tools used were enumerated based on frequency (either number of occurrences or length of time of occurrence) for each two-minute segment. The values for frequency ranged from zero (occurred zero times in the segment or occurred for zero of 120 seconds) to three (occurred >10 times in the segment or occurred for >80 of 120 seconds). Enumeration of electronic products being recycled in the sampled videos was dichotomous (yes/no) rather than a frequency scale (0-3). Five research assistants collaborated in the analysis of video footage using the developed tool. To evaluate interrater agreement, all research assistants watched the same five video segments and a kappa test of interrater agreement was run on each of set of responses to ensure a suitable level of agreement (kappa >0.6).

3.2.6 Statistical methods

Statistical tests were performed using SPSS v.25 (IBM, Armonk, New York) and Stata v.15 (StataCorp, LLC, College Station, TX). Normality of data distributions was evaluated in variables using histograms. Association between pairs of variables were made using scatterplots. Summary statistics were calculated for demographic, hearing, injury, and video variables. Independent two-sample t-tests were used to evaluate differences in continuous variables between workers in Thailand and Chile. Chi-squared tests were used to test differences in categorical variables between Thailand and Chile. For variables containing less than five observations in a category, Fisher's exact test was used. Individual-level mean frequency scores in the video data were determined by calculating the mean across all 10 repeated video observations per participant. The maximum mean score possible was 3.0, which would correspond to a participant scoring a 3 (occurred >10 times or for >80 seconds) across all ten of that participant's 2-minute video segments. The lowest possible mean score was 0, which indicated that no participant scored above a "0" for any of the ten 2-minute video segments.

Logistic regression models were developed to estimate the odds ratio (OR) of injury occurring based on e-waste recycling job tasks, PPE use, and other related variables. Poisson regression models were used to estimate incidence rate ratios for injuries using similar methods to the logistic regression models. Poisson regressions were run separately for survey and video data. Multivariate regressions were run with inclusion of significant variables from the univariate analysis.

3.3 Results

3.3.1 Demographics

A total of 130 e-waste workers were recruited for the study in Thailand, and 94 in Chile. Demographic characteristics for the participants in Thailand and Chile are displayed in Table 3-1. The Thai workers had a significantly lower mean BMI and worked significantly fewer hours per week than the Chilean workers. There were significantly more females and married workers in Thailand compared to Chile, but age, level of education, income (in PPP, a measure which allows for comparison of international monetary units by converting to the purchasing power of 1 USD), and percentage of workers reporting e-waste as the primary source of income were not statistically different.

Table 3-1 Demographic data for Thai and Chilean e-waste workers.

	Thailand		Chile	
Variable	**N**	**Mean (sd)**	**N**	**Mean (sd)**
Age	130	51.2 (4.9)	94	54.9 (8.2)
BMI	70	24.9 (0.5)***	93	30.14 (0.6)***
Years working E-waste	-	-	92	19.4 (9.1)
Hours per week	121	40.9 (15.4)*	95	50.5 (37.6)*
	N	**n (%)**	**N**	**N (%)**
Sex – Male	130	71 (54.2)**	94	68 (72.3)**
Married	128	74 (57.8)*	93	41 (44.1)*
Education – 2o and up	127	63 (49.6)	93	56 (60.2)
Income > $1250 PPP[1]	128	31 (24.2)	87	31 (35.6)
E-waste Primary Job	130	72 (55.4)	94	58 (61.7)

*p<0.05; **p<0.01; ***p<0.001. [1]PPP = Purchasing power parity (PPP) conversion factor. World Bank, International Comparison Program database. N denotes the total number of valid observations per variable, or the number of observations represented by "yes" in the dichotomous variable.

3.3.2 Noise exposures and hearing loss

Noise exposures and hearing characteristics are shown in Table 3-2. The mean and standard deviation run time for personal noise dosimetry in Chile was 5.96±1.34 hours, and 6.03±0.65 hours in Thailand (data not shown). The mean TWA noise exposure in Thailand was 70.0 dBA and was significantly higher than the mean TWA in Chile of 55.2 dBA. There were no significant differences between the two countries in the reported frequency of working in noisy environments, experiencing a TTS, or wearing PPE to protect hearing.

Table 3-2 Noise and hearing self-reported survey results from e-waste workers from Thailand and Chile.

	Thailand		Chile	
Variable	**N**	**Mean (sd)**	**N**	**Mean (sd)**
Noise TWA (dBA)	67	70.0 (36.5)**	84	55.2 (32.4)**
Years working in loud noise	88	9.2 (9.8)	68	9.53 (10.2)
	N	**N (%)**	**N**	**N (%)**
Self-reported hearing difficulty	125	33 (26.4)	92	25 (27.2)
Diagnosed poor loss	122	5 (4.1)	90	4 (4.4)
Hearing test	69		71	
Normal		37 (53.6)**		55 (77.5)**
Mild hearing loss		19 (27.5)		7 (9.9)
Moderate hearing loss		13 (18.84)		8 (11.3)
Severe hearing loss[1]		0		1 (1.4)
Perceived noisy work	95		76	
Never		23 (24.2)		19 (25.0)
Almost never		11 (11.6)		4 (5.3)
Sometimes		29 (30.5)		24 (31.6)
Almost always		25 (26.3)		22 (29.0)
Always		7 (7.4)		7 (9.21)
Temporary threshold shift	119		88	
Never		99 (83.2)		77 (87.5)
Almost never		6 (5.0)		3 (3.4)
Sometimes		10 (8.4)		5 (5.7)
Almost always		3 (2.5)		2 (2.7)
Always		1 (0.8)		1 (1.1)
Wears Ear PPE	129	5 (3.9)	93	8 (8.6)

**p<0.05.

3.3.3 Audiometric testing

Audiometric hearing threshold results are shown for Chile and Thailand in Table 3-2 and Figure 3-1. Sixty-nine workers in Thailand received a hearing test, and 71 in Chile. Thresholds of "0" in Figure 3-1 represent normal hearing at each frequency. Thresholds over 25 dB HL represent a mild hearing loss. The elevated thresholds at 500 Hz were likely due to background noise resulting from administration of the audiometric tests in a field setting, and likely do not reflect actual hearing loss at those frequencies. The frequencies considered most reflective of noise-induced hearing loss are 4,000 and 6,000 Hz; as shown in Figure 3-1, thresholds were highest (worst) at 6,000 Hz in both Chile and Thailand. There was a significant difference in categorical measures of hearing ability between Thailand and Chile, with 46.4% of Thai participants having mild or worse hearing loss compared to 22.5% in Chile.

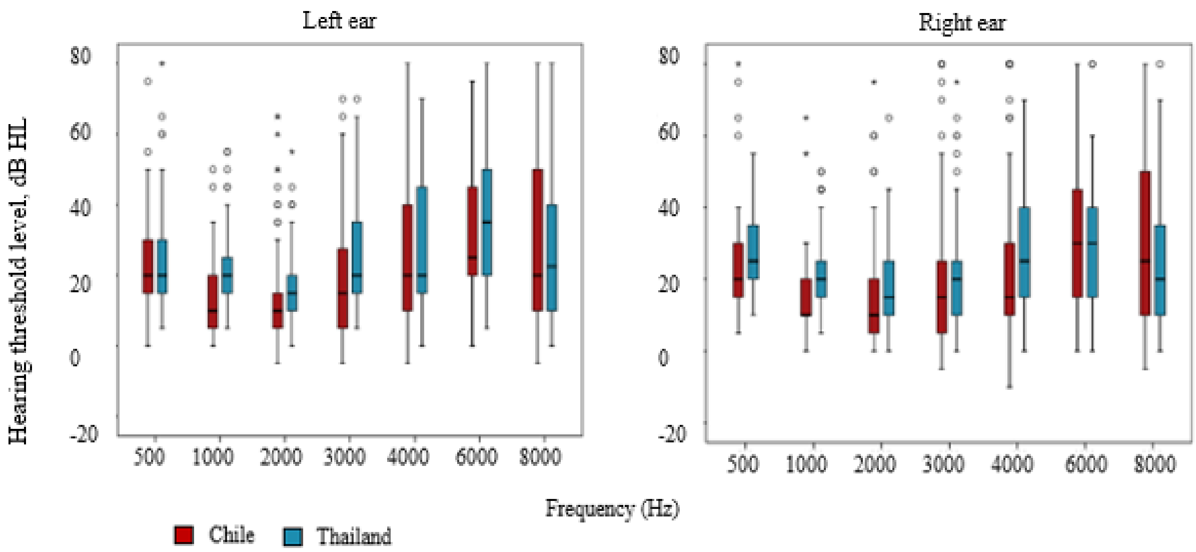


Figure 3-1 Audiometric results for electronic waste recyclers in Chile and Thailand by ear.

3.3.4 Injuries

Self-reported injury results are displayed in Table 3-3. Workers in Chile reported more than twice as many injuries (mean of 3.0 injuries) than in Thailand (mean of 1.4 injuries) during the previous six months; this different was statistically significant. While a similar number of workers reported experiencing an injury during the previous six months in Thailand and Chile (59.2% and 61.1%, respectively), significantly more workers reported being injured more than once during the same time in Chile (65.5%) compared to Thailand (42.9%). Approximately one-third of workers in each country reported seeking no medical care for their worst injury over the previous six months, while 45.6% of and 47.5% Chilean participants reported administering self-care for their injury. Approximately 75% of workers in Thailand and Chile reported wearing some type of PPE regularly. Workers in Thailand most frequently reported that use of a hammer resulted in injury, whereas workers in Chile reported the angle grinder.

Table 3-3 Self-reported injury characteristics among e-waste workers in Thailand and Chile for the previous 6 months.

	Thailand		Chile	
Variable	**N**	**Mean (sd)**	**N**	**Mean (sd)**
Number of Injuries	130	1.4 (2.4)*	95	3.0 (7.3)*
	N	**N (%)**	**N**	**N(%)**
Injured at least once	130	77 (59.2)	95	58 (61.1)
More than 1 injury	77	33 (42.9)**	58	38 (65.5)**
Medical attention	74		29	
None		25 (33.4)		20 (33.9)
Self-administered		34 (45.6)		28 (47.5)
Pharmacy		2 (2.7)		0
Hospital/clinic		13 (17.6)		11 (18.6)
Wears PPE regularly	125	89 (71.2)	93	70 (75.3)
Frequent injury	23		55	
Hammer		15 (65.2)		6 (10.9)
Blade		4 (17.4)		0
Drill		0		4 (7.3)
Angle Grinder		0		11 (20.0)
Soldering		0		9 (16.4)
Plastic		1 (4.4)		1 (1.82)
Metal		0		4 (5.5)
Dismantling		0		4 (7.3)
Collecting		0		2 (3.6)
Welding		0		3 (5.5)
Loading		0		11 (20)

*p<0.05; **p<0.01.

3.3.5 Noise exposures and injuries

The activity being performed during the worst injury in the previous 6 months is displayed by mean noise TWA for Chile and Thailand in Figure 3-2. There was no significant difference between the mean TWA across the different activities within countries. There was no difference in TWA between participants who reported an injury and those who did not (data not shown).

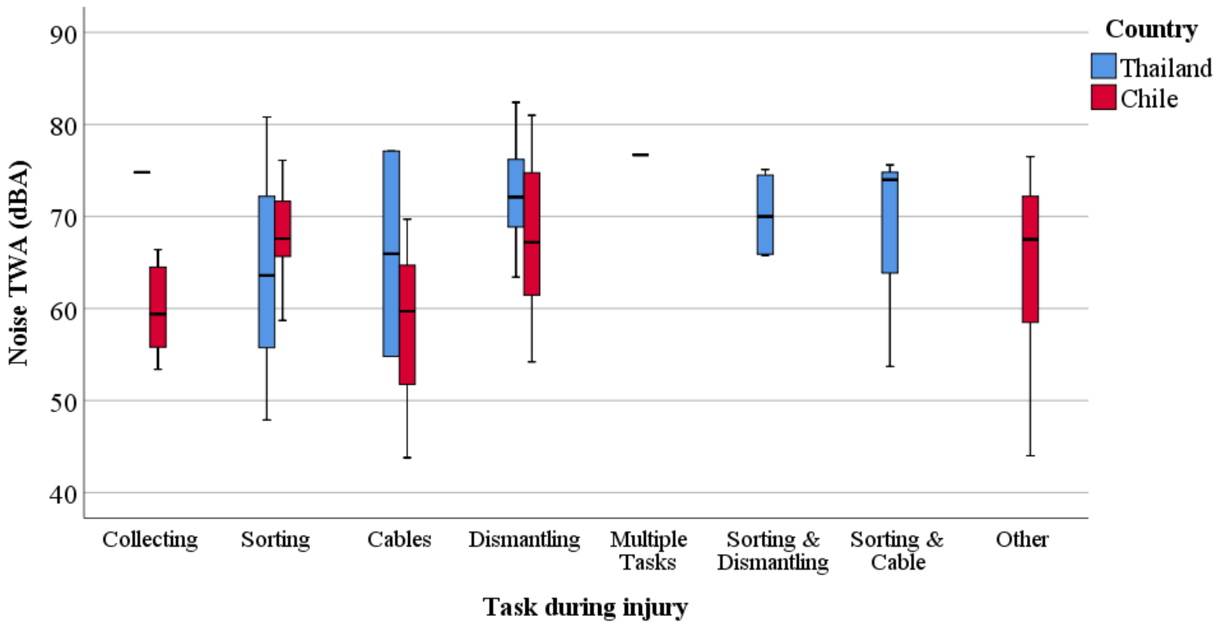


Figure 3-2 Boxplot showing measured noise level (TWA (dBA)) by e-waste recycling task being performed during time of worst injury in previous six months.

3.3.6 Worst injury in the previous six months

Figure 3-3 shows the results of self-reported injury type reported for the worst injury over the previous six months for Thailand (n=77 workers) and Chile (n=58 workers) by activity performed when the injury occurred. In Thailand, the most common type of reported worst injury was a contusion during dismantling, followed by a cut during dismantling. In Chile, the most common type of worst injury reported was a cut during dismantling, followed by a cut during sorting. Injuries counted in the “other injury” category include fractures, strains, and electrical shocks.

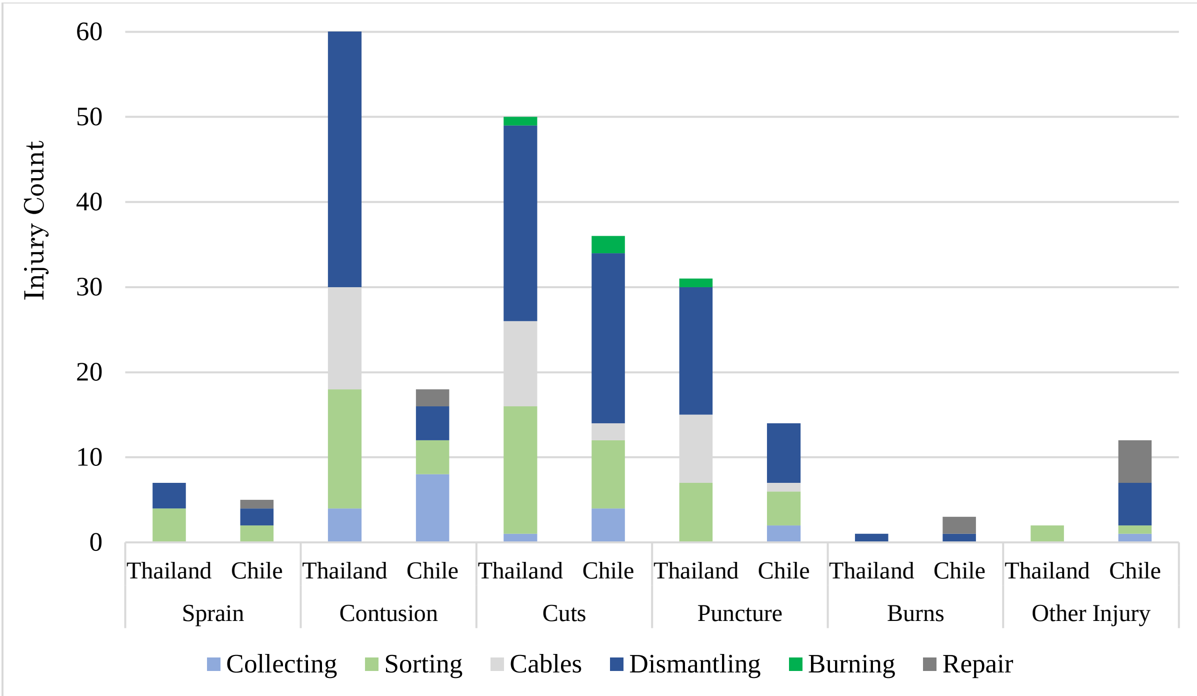


Figure 3-3 Counts by injury type and task performed during time of injury occurrence for worst injury over the previous 6 months for Thailand (n=77) and Chile (n=58) e-waste workers.

The body part injured as well as the task being performed during the worst injury sustained during e-waste recycling in the previous six months are displayed in Figure 3-4. In Thailand (n=77 workers) and Chile (n=58 workers), the body part and activity most frequently reported in both countries were the hand and dismantling, respectively.

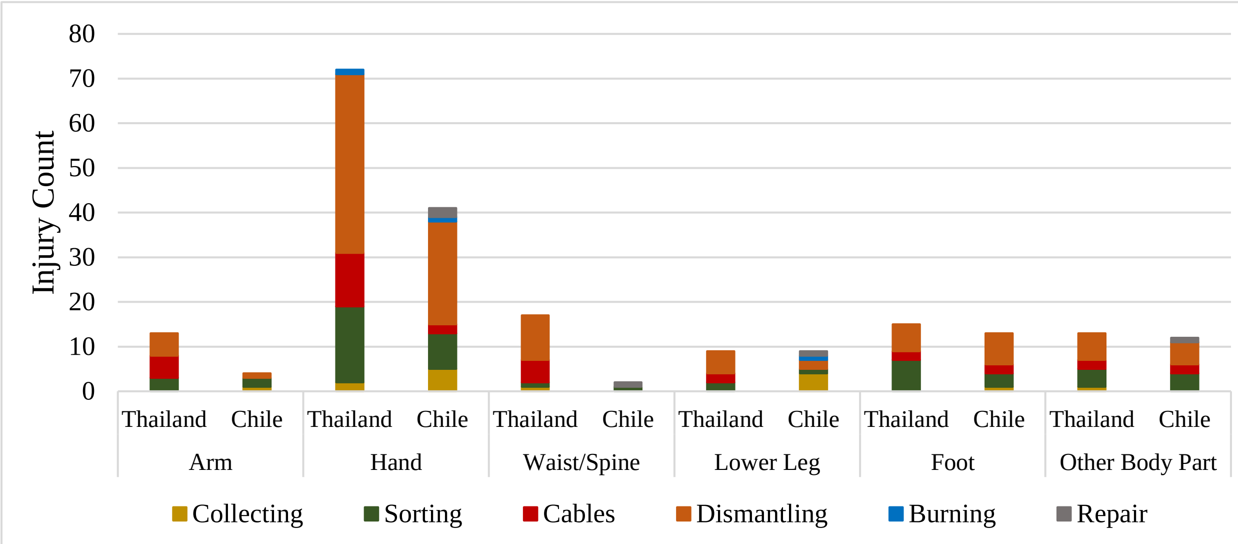


Figure 3-4 Counts by body part affected and task performed during time of injury occurrence for worst injury over the previous 6 months for Thailand (n=77) and Chile (n=58) e-waste workers.

3.3.7 Regression analysis using survey data

The results from the univariate and multivariate logistic regressions using self-reported injury data for Thailand are shown in Table 3-4. In the univariate analyses, workers who reported being exposed to perceived noise at work sometimes had an increased odds of injury (ORs of 8.44 and 5.89, respectively) compared with participants who reported never being exposed to noisy work environments. Regular use of PPE was shown to have a protective effect (OR=0.20) on injury occurrence compared to participants who did not report regularly using PPE. In the multivariate analysis, perceived noise and regular PPE use remained significant predictors of injury occurrence.

Table 3-4 Results of logistic regression for Thailand injury survey data showing the odds ratios for injury occurrence.

Variable	N	Univariate analysis OR (95% CI)	N	Multivariate analysis OR (95% CI)
Age	130	0.7 (0.3, 1.4)		
Sex - Female	130	1.0 (1.0, 1.0)		
Education[1] – Secondary and up	127	1.0 (0.5, 2.0)		
TWA	67	1.7 (1.0, 1.0)		
Perceived Noise[2]	95		91	
Almost never	11	8.4 (1.4, 49.3)*		3.7 (0.5, 28.8)
Sometimes	29	5.9 (1.8, 19.9)**		5.8 (1.6, 21.4)**
Almost always	25	2.4 (0.7, 7.7)		3.0 (0.8, 10.8)
Always	7	4.7 (0.7, 30.1)		4.6 (0.7, 29.7)
Regular PPE use	125	0.2 (0.1, 0.5)**	91	0.2 (0.1, 0.6)**

*p<0.05; **p<0.01. [1]Reference category is primary and below. [2]Reference category is Never.

Table 3-5 shows the results of univariate and multivariate logistic regressions for Chile using self-reported data on injuries. In the univariate analyses, report of a work task which frequently results in injury by participants is a significant positive predictor of injury occurrence (OR = 2.43). Participants who reported buying and selling e-waste materials had a significantly lower odds of injury occurrence (OR=0.26) compared to those who did other e-waste recycling activities. In the multivariate analysis, reporting frequently engaging in buying/selling e-waste remained significant.

Table 3-5 Results of logistic regression for Chile injury survey data showing the odds ratios for injury occurrence.

Variable	N	Univariate analysis OR (95% CI)	N	Multivariate analysis OR (95% CI))
Age	94	1.0 (1.0, 1.0)		
Sex - Female	94	0.6 (0.2, 1.0)		
Education[1] – Secondary and up	93	1.5 (0.6, 3.5)		
TWA	84	1.0 (1.0, 1.0)		
Perceived Noise[2]	76			
Almost never	4	-		
Sometimes	24	0.7 (0.2, 2.3)		
Almost always	22	0.4 (0.1, 1.4)		
Always	7	0.6 (0.1, 3.7)		
Regular PPE use	93	2.2 (0.8, 5.8)		
Frequent Injury Task	93	2.4 (1.0, 5.8)*	87	2.4 (1.0, 6.0)
Buy/Sell Task Familiarity	87	0.3 (0.1, 0.9)*	87	0.3 (0.1, 0.8)*
Years working on e-waste	92	1.0 (0.9, 1.0)		

*$p<0.05$. [1]Reference category is Primary or below. [2]Reference category is Never.

The Poisson regression results for self-reported injury data from Thailand are shown in Table 3-6. The univariate analyses show that participants aged 30 to 55 years and participants who had secondary education or higher had a significantly lower incidence rate of injury (IRR=0.6, and 0.6, respectively). Both variables remained significant in the multivariate analysis. The overall incidence rate ratio for Thailand was 1.4 injuries over 6 months.

Table 3-6 Results of Poisson regression using Thailand survey data showing the Incidence Rate Ratio for injuries.

Variable	N	Univariate analysis IRR (95% CI)	N	Multivariate analysis IRR (95% CI)
Age[1] – 30-55 years	130		127	
30-55 years	76	0.6 (0.5, 0.9)*		0.6 (0.4, 0.9)**
>55 years	30	0.7 (0.5, 1.1)		0.8 (0.5, 1.2)
Sex - Female	130	0.8 (0.6, 1.1)		
Education[2] – Secondary and up	127	0.6 (0.5, 0.8)**	127	0.6 (0.5, 0.8)**
Perceived Noise[3]	95			
Almost never	11	1.0 (0.6, 1.7)		
Sometimes	29	1.0 (0.6, 1.5)		
Almost always	25	0.8 (0.5, 1.3)		
Always	7	1.4 (0.8, 2.5)		
Regular PPE use	125	1.1 (0.8, 1.6)		

*$p<0.05$; **$p<0.01$. [1]Reference category is 18 to <30 years. [2]Reference category is primary and below. [3]Reference category is Never.

Univariate and multivariate Poisson regression results for self-reported injury data from Chile are displayed in Table 3-7. In the univariate analysis, being 30 to 55 years, as well as being

>55 years, old resulted in a significantly greater incidence of injury (IRRs=1.61 and 2.96, respectively) compared to those who were 18-29 years of age. Participants who had an education at the secondary level or higher had a significantly higher incidence rate of injury compared to those who did not (IRR=1.74). Workers who reported having one work task that more frequently results in injury had a significantly higher incidence of injury (IRR=2.03). Participants who reported working in noise reported a lower incidence of injury that those who reported never working in noise. Workers who reported frequently engaging in buying and trading e-waste had a significantly lower incidence of injury (IRR=0.28). In the multivariate analysis, age above 55, education, perceived noise, reporting a work task with higher incidence of injury, and having the most familiarity with buying and selling e-waste materials all remained significant in predicting the rate of injury incidence. The overall incidence rate ratio for Chile was 3.0 injuries over 6 months. Thailand had a rate ratio for injuries of 0.63 compared with Chile (data not shown).

Table 3-7 Results of Poisson regression using Chile survey data showing the Incidence Rate Ratio for injuries.

Variable	**N**	**Univariate analysis IRR (95% CI)**	**N**	**Multivariate analysis IRR (95% CI)**
Age[1]	94		69	
30-55 years	44	1.61 (1.08, 2.41)*		1.86 (0.96, 3.61)
>55 years	31	2.96 (2.0, 4.39)***		8.93 (4.63, 17.26)***
Sex - Female	94	0.38 (0.27, 0.54)		
Education[2] – Secondary and up	93	1.74 (1.34, 2.25)***		2.73 (1.88, 3.97)***
Perceived Noise[3]	76			
Almost never	4	0.12 (0.04, 0.36)***		0.07 (0.02, 0.23)***
Sometimes	24	0.29 (0.21, 0.42)***		0.22 (0.15, 0.32)***
Almost always	22	0.29 (0.20, 0.41)***		0.28 (0.19, 0.42)***
Always	7	0.62 (0.41, 0.93)*		0.87 (0.57, 1.33)
Regular PPE use	93	1.14 (0.81, 1.58)		
Frequent Injury Task	93	2.03 (1.55, 2.64)***		3.71 (2.62, 5.24)***
Buy/Sell Familiarity	87	0.28 (0.16, 1.48)		0.34 (0.16, 0.70)**
Years E-waste[4]	92			
2-5 years	6	1.00 (0.27, 1.37)		
5-10 years	9	3.04 (0.94, 9.81)		
>10 years	75	2.08 (0.67, 6.50)		

$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$. [1]Reference category is 18 to <30 years. [2]Reference category is primary and below. [3]Reference category is Never. [4]Reference category is <2 years.

3.3.8 Video Analysis

Mean frequency scores for different work activities are shown by country in Table 3-8. Some tasks, such as burning e-waste and breaking glass, were never recorded on video and so are not included in the results. The number of participants included in the videos was 19 in Thailand and 20 in Chile. The average number of minutes of edited video footage per participant in Thailand was 119.6, and in Chile was 72.5. The work tasks/tools most commonly reported in Thailand were blunt striking instrument (0.9) working near scrap metal (0.8). This means that, on average, workers in the videos engaged in these work characteristics between 0-3 times, or for <20 seconds. The work tasks/tools most commonly reported in Chile were working near sharp metal and working near noisy activities. On average, workers engaged in these work activities between 1 and 10 times per 2-minute video.

Table 3-8 Individual-level results of video analysis enumerating job tasks and characteristics pertinent to injury risk.

Variable	**Thailand**	**Chile**
Number of participants	19	20
Average edited footage per participant (mins)	119.6 (89.4)	72.5 (76.6)
Range edited footage per participant (mins)	44.7, 439.5	13.7, 209.1
	Score mean (sd)[1]	
Hand tool use		
Sharp blade	0.1 (0.1)	0.02 (0.1)
Blunt striking instrument	0.9 (0.6)***	0.1 (0.4)***
Screw driver	0.2 (0.2)	0.2 (0.3)
T-wrench	0.1 (0.2)	0
Wrench	0.02 (0.1)	0.2 (0.1)
Pliers/scissors	0.3 (0.3)*	0.1 (0.2)*
Bolt cutters	0.01 (0.1)	0
Chisel	0.2 (0.3)	0.1 (0.3)
Other – At least one other type of tool	0.1 (0.2)	0
Power tool use		
Power drill	0.2 (0.3)	0.03 (0.1)*
Soldering iron	0	0.1 (0.2)
Ergonomics		
Repetitive hand motion	0.5 (0.8)	0.2 (0.4)
Repetitive arm motion	0.5 (0.6)*	0.1 (0.2)*
Constant grip	0.8 (1.0)	0.4 (0.7)
Lifting <20 pounds	0.4 (0.6)	0.6 (1.3)
Lifting >20 pounds	0.6 (0.7)	0.6 (1.3)
Bending neck	1.9 (0.7)	1.4 (2.0)
Bending back	1.4 (1.1)	1.5 (1.9)
Squatting/kneeling	0.8 (1.2)*	0.2 (0.5)*
Sitting low to ground	1.8 (1.3)***	0.02 (0.05)***
Pushing/pulling	0.1 (0.2)	0.3 (0.9)
Work tasks		
Removing broken glass from electronic	0.3 (0.8)	0
Working near broken glass	0.5 (1.0)*	0.02 (0.1)*
Working near sharp metal	0.8 (1.3)	1.3 (4.0)
Removing sharp metal from electronic	0.1 (0.3)	0.01 (0.04)
Handling/moving sharp metal	0.1 (0.4)	0.04 (0.1)
Noisy activities	1.3 (0.9)*	0.7 (0.9)*
PPE use		
Cotton gloves	2.0 (1.4)	1.4 (4.1)
Latex gloves	0.4 (1.1)	0.6 (1.3)
Close-toed shoes	1.3 (1.4)***	3.3 (1.6)***
Dust mask	0.2 (0.7)	0
Fabric as mask	0.3 (0.8)	0
Long sleeves	2.2 (1.3)	2.7 (0.7)
Long pants	2.2 (1.3)	2.7 (0.7)
Hearing protection	0	0
Electronic product	**Mean (sd)**	
Cathode ray tube TV	0	0.03 (0.1)
Refrigerator	0	0
Washing machine	0	0.03 (0.1)
Electric fan	0.3 (0.4)	0
Desktop monitor -CRT	0.01 (0.02)	0.01 (0.03)
Desktop monitor or TV-flat screen	0	0.1 (0.2)
Computer tower	0.01 (0.03)	0.01 (0.1)
Cell phone	0	0.2 (0.6)
Laptop	0	0.01 (0.02)
Printed circuit board	0	0.1 (0.2)
Parts	0.8 (0.4)	0.7(1.3)
Other – At least one other type of electronic	0.02 (0.1)	0.2 (0.5)

The cumulative scores across categories from the video analysis are displayed in Figure 3-5. Section 3-5a shows the cumulative frequency for tools used in each country. In Thailand, blunt striking instruments, such as hammers, had the highest frequency of use, while in Chile, the most frequently used tool was the screw driver. The “other” hand tools in each country was mostly comprised of specialized types of wrenches. In Chile, the “other” power tool category included heat guns. Section 3-5b shows that the most common ergonomic factor in Thailand was bending of the back, followed closely by sitting low to the ground and bending the neck. In Chile, the most frequent ergonomic factors included bending of the neck and back, followed by constant hand grip.

Section 3-5c displays different observed work tasks/hazards. Noisy environments and working near scrap metal had the highest cumulative frequency in both Thailand and Chile. Section d shows that use of long-sleeve shirts, long pants, and closed-toed shoes was common in each country, as was use of cotton gloves in Thailand. The “other” category of PPE in Chile included protective eye wear and a helmet.

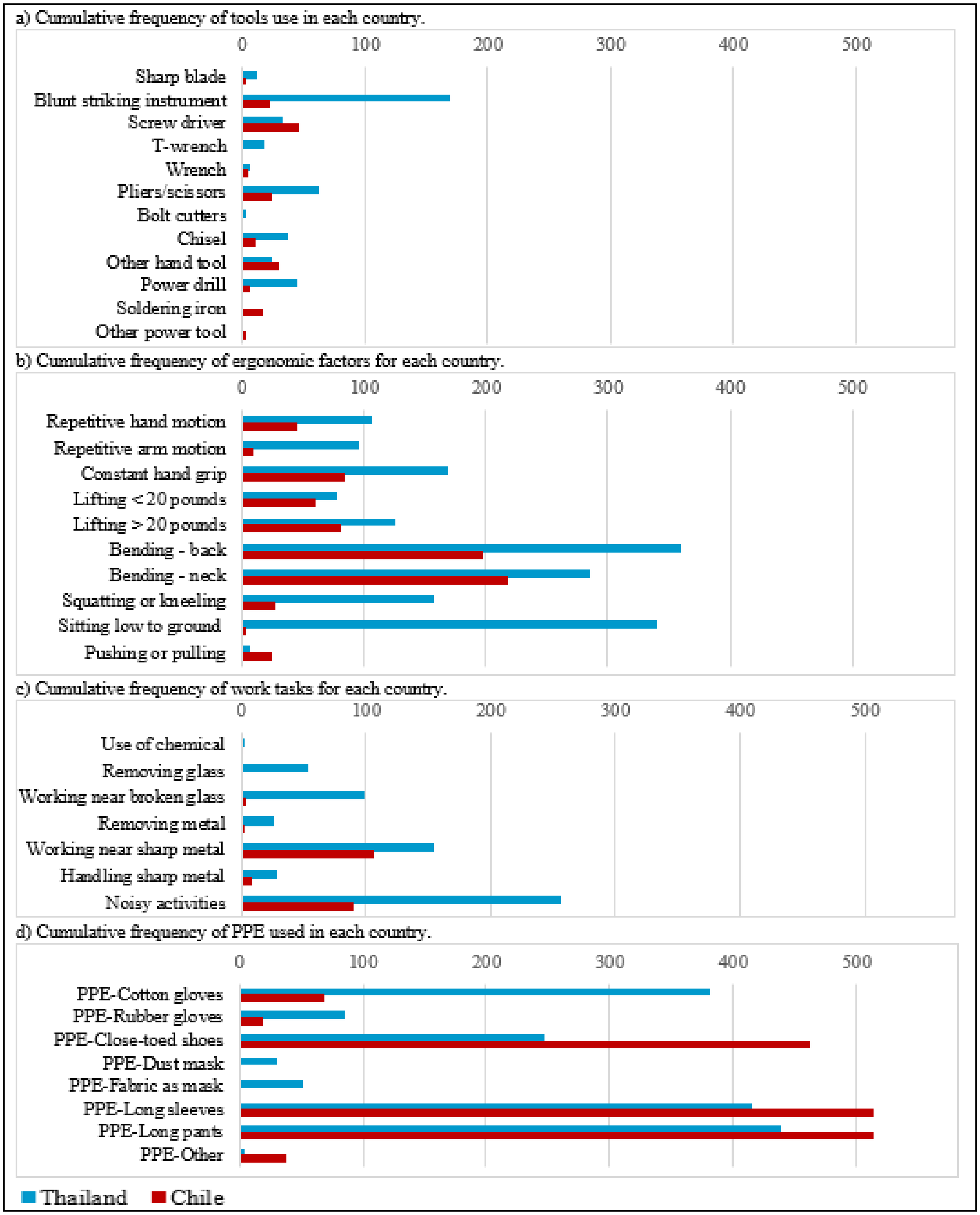


Figure 3-5 Cumulative frequency results of video analysis enumerating job tasks and characteristics pertinent to injury risk.

As shown in Table 3-9, the univariate Poisson regression in Chile produced two predictors that had a significantly lower rate of injury incidence, including work on a flat screen monitor (IRR=0.02), and work on a cell phone (IRR=0.4). Significant predictors of increased rate of injury incidence included repetitive arm motion (IRR=3.8), lifting less than 20 pounds (IRR=1.3), bending of the back and neck (IRR=1.2 and 1.2, respectively), pushing or pulling (IRR=1.4), as well as working near sharp metal (IRR=1.1) and use of cotton gloves as PPE (IRR=1.1). Results from the Thailand univariate Poisson regression using video-derived data shows that use of pliers/scissors was associated with an increased incidence of injury (IRR=3.4).

Cell phones remained a significant predictor in the multivariate logistic regression shown in Model 2 of Table 3-10 (OR=0.3). Two models were built using the univariate Poisson regression results for Chile. Model 3 in Table 3-10 includes variables that were the most significant and most likely to cause wound-type injuries. These included the use of cotton gloves (IRR=1.2) and working near sharp metal (0.9). Model 4 included significant predictors of ergonomic or strain type injuries. Repetitive arm motion was significantly associated with an increased incidence of injury (IRR=9.2), as was lifting of less than 20 pounds (IRR=8.3).

Table 3-9 Results of univariate analysis using Poisson (incidence rate of injuries) regression for quantitative injury and task data derived from videos.

	Thailand	**Chile**
Variable	**IRR (95% CI)**	**IRR (95% CI)**
Hand tool use		
Sharp blades	9.4 (0.8, 108.2)	-
Blunt striking	1.7 (0.9, 3.1)	1.1 (0.8, 1.5)
Screwdriver	0.5 (0.1, 3.0)	1.0 (0.6, 1.7)
T-wrench	4.9 (0.3, 76.6)	-
Wrench	-	26.7 (0.05, 15629.3)
Pliers/scissors	3.4 (1.1, 10.8)*	0.1 (0.01, 2.3)
Bolt cutters	-	-
Chisel	1.2 (0.4, 3.4)	1.3 (0.8, 2.1)
Power tool use		
Power drill	1.9 (0.7, 5.1)	-
Soldering iron	-	3.9 (0.2, 84.9)
Ergonomics		
Repetitive hand motion	1.0 (0.7, 1.4)	1.8 (0.8, 1.5)
Repetitive arm motion	1.5 (0.9, 2.4)	3.8 (1.8, 7.8)***
Constant grip	1.1 (0.8, 1.5)	2.2 (0.9, 5.3)
Lifting <20 pounds	1.6 (0.9, 2.9)	1.3 (1.2, 1.4)***
Lifting >20 pounds	0.7 (0.5, 1.1)	1.3 (0.9, 1.9)
Bending back	1.9 (0.8, 4.0)	1.2 (1.0, 1.3)*
Bending neck	1.2 (0.9, 1.5)	1.2 (1.1, 1.4)***
Squatting/kneeling	0.9 (0.7, 1.2)	1.8 (1.0, 3.4)†
Sitting low to ground	1.2 (0.9, 1.5)	-
Pushing/pulling	1.7 (0.7, 4.3)	1.4 (1.1, 1.7)**
Work tasks		
Removing broken glass	0.8 (0.5, 1.4)	-
Working near broken glass	1.0 (0.7, 1.4)	-
Removing sharp metal	0.8 (0.2, 2.7)	-
Working near sharp metal	1.3 (1.0, 1.6)†	1.1 (1.0, 1.1)*
Handling sharp metal	0.7 (0.2, 2.3)	4.1 (0.03, 512.4)
Noisy activities	1.1 (0.8, 1.7)	1.3 (0.9, 1.8)
PPE		
Cotton gloves	1.1 (0.8, 1.5)	1.1 (1.0, 1.1)*
Latex gloves	0.8 (0.5, 1.3)	1.2 (0.8, 1.9)
Electronic product		
Electric fan	0.8 (0.3, 1.8)	-
Flat screen monitor	-	0.02 (0.002, 0.4)**
Cell phone	-	0.4 (0.2, 0.9)*
PCB	-	4.8 (0.1, 244.7)
Parts	2.2 (0.6, 8.0)	1.2 (0.9, 1.5)

*p<0.05; **p<0.01; ***p<0.001. †0.05<p<0.055

The multivariate models in Table 3-10 selected from the significant predictors in Table 3-9 to predict the incidence rate of injuries (Poisson regression). The Poisson regression for Thailand, Model 1 in Table 3-10, included two predictors, use of pliers/scissors and working near sharp metal, which were significant (or nearly so) in the univariate models. Both predictors lost significance in the multivariate analysis. Models 2 and 3 are Poisson regression models for the Chilean data set. Model 2 focuses on traumatic injury predictors, while Model 3 looks at ergonomic stressors. In Model 2, use of cotton gloves was unexpectedly significantly associated ($p<0.05$) with a 1.2 higher incidence rate compared to workers who do not use cotton gloves (but could potentially be using other types of gloves). Working near sharp metal lost significance in the model. The ergonomic stressors in Model 3 show that repetitive arm motion and lifting less than 20 pounds were each significantly associated with increased rates of injury incidence compared to workers who do not perform these tasks (IRR=9.2 and 8.3, respectively).

Table 3-10 Results of multivariate analysis using Poisson regression for quantitative injury and task data derived from videos.

Poisson Regression Model	**IRR (CI)**
	Thailand
Model 1	IRR (CI)
Constant	0.9 (0.5, 1.7)
Pliers/Scissors	2.9 (0.9, 10.0)
Working near sharp metal	1.2 (0.9, 1.5)
	Chile
Model 2	IRR (CI)
Constant	7.3 (3.0, 17.6)***
Cotton gloves	1.2 (0.8, 1.7)*
Working near sharp metal	0.9 (0.6, 1.3)
Model 3	IRR (CI)
Constant	2.8 (1.2, 6.4)*
Repetitive arm motion	9.2 (3.6, 23.3)***
Lifting <20 pounds	8.3 (1.5, 47.8)*

$^{*}p<0.05$; $^{***}p<0.001$

3.4 Discussion

This study examined occupational noise exposure and NIHL among informal e-waste recyclers, and also examined the risk of injury associated with specific tools, tasks, and other job features characteristic of e-waste recycling. In addition to providing novel information about the prevalence of NIHL and injuries, this study is the first to provide a detailed, quantitative analysis on the hazards of e-waste recycling through prediction of odds ratios and incidence rate ratios of injury occurrence by specific job features. The use of a novel video tool to create a quantitative data set of the work tasks, tools, ergonomic stressors, PPE use, and other physical stressors provided information about the frequency with which different hazards are used by informal e-waste workers, as well as the risk of injury of each.

3.4.1 Demographics

The demographic characteristics of our sample confirm that these informal e-waste workers are a marginal and vulnerable community. Most of our participants reported a monthly household income below $1,250 PPP. In comparison, the United States had an average monthly wage for full-time equivalent workers of $4,893 PPP in 2015 [43]. Additionally, approximately half of workers in each country did not have a high school education. Reports and studies from other parts of the world have similarly reported that e-waste workers tend to be from lower socioeconomic segments of the population [17], [18], [35], [37], [44]-[47]. Workers in Thailand reported an average of 41 hours worked per week, while in Chile the mean was 51 hours per week. Notably, more than half of workers in each country reported e-waste recycling as their primary job, meaning that many workers likely work many more hours per week when secondary jobs are considered.

3.4.2 Noise and hearing

The mean TWA (dBA) in each country was well below the Recommended Exposure Limit of 85 dBA set by NIOSH [48]. These results were in contrast to those reported by Burns, et al., 2016, which reported that 40% of e-waste workers surveyed in Accra, Ghana were exposed to TWA noise levels > 85 dBA [36]. However, exposure to brief but intense transient noises has been shown to increase risk of NIHL in workers even when the TWA is below 85 dBA [49]-[50].

Results from the audiometric tests show that participants in Chile had a similar rate of hearing loss, 22.5%. However, 46.4% of participants in Thailand had mild or worse hearing loss. The higher rates of hearing loss as well as the higher TWA in Thailand might be explained by transient noise exposure; such exposures were observed frequently among e-waste workers in Thailand who often use rudimentary, hand-made tools. Approximately 23% of noise-exposed workers in the U.S. have hearing loss, and 5% report tinnitus [51].

Although no association was found between noise TWA and injuries, there was an association found between self-reported perceived noise and injury rate in Thailand. As the level of perceived noise frequency increased, with the exception of the highest frequency level, the odds ratio decreased, suggesting that less noisy environments resulted in more injuries (Table 3-4). This finding directly contradicts studies that show a dose-response relationship between noise and injury in occupational settings [51]-[52]. One possible explanation is that workers in quieter settings are more likely to work alone and injure themselves when they are unable to seek assistance for a task. Alternatively, the tasks associated with the greatest risk of injury in e-waste recycling may be quieter tasks. An example of this is found in the multivariate regressions in Table 3-10, where we see working near sharp metal as a predictor of increased injury incidence rate in Thailand. Merely working near sharp metal is not necessarily associated with any level of noise. More information and repeated measurements are needed to determine the difference in noise exposure by task in order to better protect workers [53].

3.4.3 Injury

Nearly two-thirds of workers in Thailand and Chile reported an injury in the previous six months. The results of the injury findings were consistent with those among a group of informal e-waste workers in Nigeria, who reported a 68% prevalence of injuries in the preceding six months [42]. Th prevalence of occupational injury in both research populations in this study is higher than that found in a group of 2,907 informal workers in Brazil, where the annual incidence rate was 6.2 injuries per 100 full-time equivalent workers [53].

The body part with the highest number of reported injuries for the previous six months in both Thailand and Chile was the hand. This finding is consistent with occupational injury reports in the United States, where 33% of emergency room visits for occupational injuries are for hand trauma [54]. Although approximately 75% of workers in each country reported regular use of PPE (presumably to reduce injury risk), this did not match our field observations. Workers also frequently used PPE in the videos of work activities; however, this again did not match our field observations and may not be representative of typical workplace behaviors. The PPE that was observed, for example cotton and latex gloves, are not suitable for protecting workers against many types of hazards associated with e-waste. In Model 3 of Table 3-10, use of cotton gloves was associated with 1.2 times higher incidence of injury compared to workers who did not wear cotton gloves in the video. The association between cotton gloves and increased incidence rates might be explained by false confidence in protection from injury resulting from the use of cotton gloves, where workers believe they are protected but the cotton glove is not adequately protective against cuts, punctures, burns, etc.

In both Thailand and Chile, access to PPE may be limited and, per conversations with workers in each country, is funded by the worker as a personal expense. The video enumeration for PPE use showed that many participants wore long pants and sleeves. This may vary seasonally in Chile, as it was winter when the study occurred. In Thailand it is unlikely to differ by season, given the relatively invariant temperatures across the year, but such PPE may be worn to preserve personal hygiene rather than as protection against injury. In both countries, the use of specific clothing is likely not sufficient to protect against all injuries.

When asked what activity was being performed during their worst injury in the previous six months, workers in Thailand most commonly identified dismantling and sorting, while Chilean workers named collection and sorting most frequently (Figure 3-3). In conversations with Chilean e-waste workers, traffic accidents during collection of curbside e-waste and lifting of heavy e-waste equipment were among the hazards identified during collection. More than half of workers in Thailand reported use of a hammer as the task they believe most frequently results in injury (Table 3-3). The IRR in the univariate analysis for video data from Thailand found that use of a blunt striking instrument (such as a hammer) had an incidence rate ratio of 1.7; however, it was not significant (95% CI = 0.9, 3.1) (Table 3-9).

The results of the self-report injury regressions (Table 3-4, Table 3-5, Table 3-6, and Table 3-7) showed several trends. In the Poisson regressions for self-reported survey data for each country, age was significantly associated with injury incidence; however, the trends for the two countries were in opposite directions. In Thailand, our results were consistent with other studies that show that younger workers, who might have less experience, tend to have higher rates of injury than older workers [55]. In Chile, workers who were aged 30 to 55 years had a 1.61 higher incidence rate, and those aged more than 55 years had a 2.96 higher incidence rate, than workers who were 18 to >30 years old in the multivariate analysis. This might be explained by the prevalence of repair of electronics observed in Chile, where workers would sometimes repair parts or rebuild electronic products using parts from other waste electronics. Repair workers require technical training, and from field observations, tended to be younger, whereas collectors and recyclers tended to be untrained and from older generations. However, more research is needed to determine why age in Chile is associated with higher incidence of injury.

The results from Chile showed an increased odds and incidence rate of injury for workers who reported that one of their work tasks results in more frequent injury. This finding suggests that the knowledge of e-workers about their own job tasks might be an informative, and perhaps better, source of injury assessment data than what can feasibly be obtained through observation.

Workers who identified buying and selling of e-waste products and materials as a task with which workers engaged in regularly was a significant predictor of lower odds and incidence of injury. This fits with field observations where the workers who were responsible for buying and selling were usually of higher rank in the work place and did not engage in dismantling and other activities as frequently as lower-rank workers. Similar systems of job task differences exist in Ghana, where scrap dealers collect a large portion of the income but do minimal dismantling and collecting work [56].

The cumulative task frequencies derived from video data in Figure 3-5 showed a high number of ergonomic stressors in each country. There is a lack of studies on ergonomic stressors in e-waste workers; however, other studies have demonstrated a serious impact on worker physical and economic health in the presence of workplace ergonomic stressors [57]. Our field observations revealed several concerning ergonomic issues, particularly in Thailand, where workers often sit on small buckets near to the ground to perform their work. In Chile, where work benches were seen more often, workers were observed to be bent over their work space, producing strain in the back and neck. In both countries we observed potential hand-arm vibration, static grip, and repetitive motion exposures.

The univariate logistic regressions shown in Table 3-9 reveal that workers who were more frequently observed recycling cell phones had an incidence rate that was 0.2 times lower than those who were less frequently observed recycling cell phones ($p<0.01$). This predictor maintained significance in the multivariate regression in Model 2 of Table 3-10. The univariate Poisson regression for Chile shows that participants who more frequently recycled flat screen monitors and cell phones had lower incidence rates of injury (IRR=0.02, $p<0.01$; and IRR=0.4, $p<0.05$, respectively). These findings suggest that product type influences injury hazard.

The univariate Poisson regressions for Thailand and Chile using video data (Table 3-9) each found an association between working near sharp metal and increased incidence rate of injury (IRR=1.1, $p<0.05$ in Chile; IRR=1.3, $0.05<p<0.055$ in Thailand). Increased injury incidence rates due to the lack of occupational hygiene and housekeeping in workplace settings has been reported in studies of other occupational groups [58], [59]. However, this variable lost significance in the multivariate models in both countries (Table 3-10). Sharp materials, like scrap metal and broken glass, present important hazards in the workplace [60]. This suggests that a relatively simple and immediate safety intervention that workers can implement themselves is to simple improving workplace housekeeping.

There was a difference in the significance of predictor variables in the Poisson regressions for the self-reported and the video data. For example, the Poisson regression in Thailand using self-reported survey data included perceived noise as a significant predictor for injury, while the Poisson regression built off of video data showed noise was not a significant risk of injury. This may be because of the variability in tasks among e-waste worker, or because the enumeration of video noise levels was based on the viewer’s subjective decision about how noisy activities in the video are rather than actual noise measurements. The use of self-report and surveillance data together revealed that different methods are useful for assessing certain aspects of e-waste recycling from an occupational safety standpoint. Personal recall proved to be effective for determining which job titles and demographic data are associated with injuries, while observational (video) data was useful in predicting which tools, tasks, ergonomic stressors, and product types present an occupational injury hazard.

3.4.4 Limitations

As with any research, this study has a number of limitations. First, the data collected during our field visits may not have been representative of a typical day of work for our study populations. Many of the analyses in this study assumed that individual worker tasks, work on types of products, and personal behaviors are static over time. Similarly, for injury self-report data, we assumed that the tasks workers performed over the previous 6 months are the same or similar to what we enumerated using the video tool. If workers were performing different tasks than normal, or if there is a great deal of variation in their work tasks, then our results would not be representative. However, based on observations at field sites and conversations with individual participants in each country, workers appear to perform similar routine tasks and do not frequently change their work habits.

The second limitation is the ability of workers to accurately recall the number of injuries over the previous six months, as well as the task performed when the injury occurred, will affect the validity of our outcome variable and results. Because our outcome variable for the Poisson regression was the injury count in the previous six months, the validity of our findings depends on the ability of workers to recall even minor injuries in detail. Additionally, it is possible that there are differences in the perception of what constitutes an injury between countries as well as between individuals, and so there may a reporting bias in the outcome injury variables. If one group was more likely to over- or under-report injuries, then our results are biased. Third, the number of participants included in the video analysis data was low in each country, limiting the validity of the findings. Workers captured on video may have been subject to observation bias, changing their work behavior because they are being recorded. We were unable to capture some of the more dangerous tasks, such as burning e-waste or breaking and removing broken glass from e-waste, in our video footage. These activities likely carry a high risk of injury that we were unable to represent in our study.

3.4.5 Future Directions

The results of this research suggest several potential future directions. First, more work is needed to compare non-auditory outcomes, such as blood pressure, with noise exposure in e-waste recyclers. Long-term exposure to environmental noise, such as that found in communities where e-waste recycling is prevalent, can result in negative cardiovascular outcomes at noise levels lower than those where NIHL is expected [61], [62]. Additionally, further studies are needed to measure impulsivity or "peakiness" in noise exposures in each site, as well as to evaluate the link between hearing loss and peak noise exposures among workers. Next, future studies should focus on conversations with workers to help determine hazardous tasks, as workers demonstrated knowledge about the physical hazards of their work. Community-based participatory research approaches that examine behaviors of e-waste workers and use their knowledge would allow researchers who are less familiar with e-waste recycling work to better select for variables to use in risk assessments of e-waste recycling. Inclusion of the more hazardous work tasks that could not be assessed in the current study (e.g., burning e-waste and use of acid baths for recycling) in future studies will help contextualize the hazards of other dismantling tasks and provide a more complete picture of injury risks in e-waste recycling. However, due to the illegality or socially unacceptable nature of these activities, such research will likely be difficult to conduct. Future ergonomic studies should address the lack of proper posturing of e-waste workers to protect against this type of injury. Finally, to determine the representativeness of our samples with regard to injury occurrence and frequency, a follow-up study with existing participants would provide information on the variability in the incidence of e-waste injuries over time.

3.5 Conclusions

This study was the first quantitative assessment of occupational injury hazards among informal e-waste workers. The study also developed and applied a novel method to enumerate observational video data into a quantitative data set allowed for analysis of the association between frequency of different job tasks and attributes and injury incidence rates. Measured noise exposures (TWA) of workers were below the limit recommended by NIOSH, though evidence of NIHL was found in audiograms. There was no association between TWA and injury; however, an association was found between self-reported occupational noise exposures and injury. Approximately 60% of e-waste workers surveyed in Chile and Thailand reported having at least one occupational injury in the past 6 months, with 43% in Thailand and 66% in Chile reporting more than one injury in the same time period. Results from this study suggest that worker age, education, job task, PPE, ergonomic stressors, and e-waste product type have an impact on the occurrence and rate of injury incidence. Collectively, these findings highlight the need for effective interventions to improve workplace safety, hygiene, and health behaviors for e-waste workers. Interventions to provide education to workers on the importance and execution of properly using PPE and maintaining proper workplace hygiene could reduce the number of hazards surrounding workers and would empower workers to protect their own health.

3.6 Bibliography

1. International Labour Organization. Safety and health at work. Available at: https://www.ilo.org/global/topics/safety-and-health-at-work/lang--en/index.htm. (Accessed: 1st January 2019)
2. Swartz, G. Job hazard analysis. Occup. Saf. Heal. Adm. 2002, 1–3 (2002).
3. Schill, A. L. & Chosewood, L. C. The NIOSH total worker health program: An overview. J. Occup. Environ. Med. 55, 10–13 (2013).
4. Lawal, A. O. Air particulate matter induced oxidative stress and inflammation in cardiovascular disease and atherosclerosis: The role of Nrf2 and AhR-mediated pathways. Toxicol. Lett. 270, 88–95 (2017).
5. Concha-Barrientos, M., Nelson, D. I., Fingerhut, M., Driscoll, T. & Leigh, J. The global burden due to occupational injury. Am. J. Ind. Med. 48, 470–481 (5AD).
6. Loewenson, R. H. Health impact of occupational risks in the informal sector in Zimbabwe. Int. J. Occup. Environ. Health 4, 264–274 (1998).
7. Alli O. Benjamin. Fundamental Principles of Occupational Health and Safety. (2008). doi:10.1017/CBO9781107415324.004
8. LaDou, J. International occupational health. Int. J. Hyg. Environ. Health 206, 303–313 (2003).
9. Lucchini, R. G. & London, L. Global occupational health: Current challenges and the need for urgent action. Ann. Glob. Heal. 80, 251–256 (2014).
10. Levy, B. S. Global occupational health issues: Working in partnership to prevent illness and injury. AAOHN J. 44, 244–7; discussion 247 (1996).
11. Balde, C. P., Forti, V., Gray, V., Kuehr, R. & Stegmann, P. The global e-waste monitor 2017. The Global E-waste Monitor (2017).
12. Ladou, J. & Lovegrove, S. Export of electronics equipment waste. Int. J. Occup. Environ. Health 14, 1–10 (2008).
13. Robinson, B. H. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–91 (2009).
14. Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M. & Böni, H. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25, 436–458 (2005).
15. Pinto, V. N. E-waste hazard: The impending challenge. Indian J. Occup. Environ. Med. 12, 65–70 (2008).

16. Bakhiyi, B., Gravel, S., Ceballos, D., Flynn, M. A. & Zayed, J. Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges. Environ. Int. 110, 173–192 (2018).

17. Perkins, D. N., Brune Drisse, M.-N., Nxele, T. & Sly, P. D. E-waste: a global hazard. Ann. Glob. Heal. 80, 286–95 (2014).

18. Heacock, M. et al. E-waste and harm to vulnerable populations: A growing global problem. Environ. Health Perspect. 550, 550–555 (2015).

19. Quinlan, M., Mayhew, C. & Bohle, P. The global expansion of precarious employment, work disorganization, and consequences for occupational health: A review of recent research. Int. J. Heal. Serv. 31, 335–414 (2001).

20. Nelson, D. I., Nelson, R. Y., Concha-Barrientos, M. & Fingerhut, M. The global burden of occupational noise-induced hearing loss. Am J Ind Med 48, 446–458 (2005).

21. Rabinowitz, P. M. Noise-induced hearing loss. Am. Fam. Physician 61, 2759–2760 (2000).

22. NIOSH. Criteria for a recommended standard: occupational noise exposure. DHHS (NIOSH) Publication Number 98-126. (1998).

23. Clark Charlotte, Mathias Basner, Wolfgang Babisch, Adrian Davis, Mark Brink, Sabine Janssen, Stephen Stansfeld, S. S. Auditory and non-auditory effects of noise on health. Lancet 12, 1325–1332 (2014).

24. van Dijk, F. J. H., Souman, a. M. & de Vries, F. F. Non-auditory effects of noise in industry. Int. Arch. Occup. Environ. Health 59, 133–145 (1987).

25. Passchier-Vermeer, W. & Passchier, W. F. Noise exposure and public health. Env. Heal. Perspect 108 Suppl, 123–31. (2000).

26. Melamed, S., Fried, Y. & Froom, P. The joint effect of noise exposure and job complexity on distress and injury risk among men and women: The cardiovascular occupational risk factors determination in Israel study. J. Occup. Environ. Med. 46, 1023–1032 (2004).

27. Dantley, L. F. et al. Association between ambient noise exposure, hearing acuity, and risk of acute occupational injury. Scandanavian J. Work Environ. Heal. 41, 75–83 (2015).

28. Neitzel, R., Long, R., Sun, K., Sayler, S. & von Thaden, T. Injury risk and noise exposure in firefighter training operations. Ann Occup Hyg Accepted, (2015).

29. Yoon, J.-H., Roh, J., Kim, C.-N. & Won, J.-U. The risk of occupational injury increased according to severity of noise exposure after controlling for occupational environment status in Korea. 2Noise Heal. 18, 355–361 (16AD).

30. Cantley, L. F. et al. Association between ambient noise exposure, hearing acuity, and risk of acute occupational injury. Scandanavian J. Work Environ. Heal. 41, 75–83 (2015).

31. Girard, S. A. et al. Occupational noise exposure and noise-induced hearing loss are associated with work-related injuries leading to admission to hospital. Inj. Prev. 21, e88–e92 (2015).

32. Picard, M. et al. Association of work-related accidents with noise exposure in the workplace and noise-induced hearing loss based on the experience of some 240,000 person-years of observation. Accid. Anal. Prev. 40, 1644–1652 (2008).

33. Girard, S. A. et al. Multiple work-related accidents: tracing the role of hearing status and noise exposure. Occup. Environ. Med. 66, 319–324 (2009).

34. Heacock, M. et al. E-Waste and harm to vulnerable populations: a growing global problem. Environ. Health Perspect. 124, 550–556 (2015).

35. Grant, K. et al. Health consequences of exposure to e-waste: a systematic review. Lancet. Glob. Heal. 1, e350-61 (2013).

36. Burns, K. N., Sun, K., Fobil, J. N. & Neitzel, R. L. Heart rate, stress, and occupational noise exposure among electronic waste recycling workers. Int. J. Environ. Res. Public Health 13, (2016).

37. Annamalai, J. Occupational health hazards related to informal recycling of E-waste in India: An overview. Indian J. Occup. Environ. Med. 19, 61–65 (2015).

38. Akormedi, M., Asampong, E. & Fobil, J. N. Working conditions and environmental exposures among electronic waste workers in Ghana. Int. J. Occup. Environ. Health 19, 278–286 (2013).

39. Yu, E. A., Akormedi, M., Asampong, E., Meyer, C. G. & Fobil, J. N. Informal processing of electronic waste at Agbogbloshie, Ghana: workers' knowledge about associated health hazards and alternative livelihoods. Glob. Health Promot. 0, 1–9 (2016).

40. Mishra, S., Shamanna, B. R. & Kannan, S. Exploring the awareness regarding e-waste and its health hazards among the informal handlers in Musheerabad area of Hyderabad. Indian J. Occup. Environ. Med. 21, 143–148 (2017).

41. Burns, K., Sayler, S. K., Neitzel, R. L. Stress, health, noise exposures and injuries among electronic waste recycling workers in Ghana. J. Occ. Med and Tox 14(1).

42. Ohajinwa, C. M. et al. Prevalence and injury patterns among electronic waste workers in the informal sector in Nigeria. Inj. Prev. 24, 185–192 (2018).

43. United Nations Economic Commission for Europe. Gross average monthly wages by country and year. (2015). Available at: http://w3.unece.org/PXWeb2015/pxweb/en/STAT/STAT__20-ME__3-MELF/60_en_MECCWagesY_r.px/?rxid=0806c85a-23f8-4249-a4d0-10980df459d1. (Accessed: 1st January 2019)

44. Grant, R. & Oteng-Ababio, M. Mapping the Invisible and Real 'African' Economy: Urban E-Waste Circuitry. Urban Geogr. 33, 1–21 (2012).

45. Amankwaa, E. F. Livelihoods in risk : exploring health and environmental implications of e-waste recycling as a livelihood strategy in Ghana *. J. Mod. Afr. Stud. 51, 551–575 (2013).

46. Wang, F. et al. The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag. 32, 2134–2146 (2012).

47. Chi, X., Streicher-Porte, M., Wang, M. Y. L. & Reuter, M. a. Informal electronic waste recycling: a sector review with special focus on China. Waste Manag. 31, 731–42 (2011).

48. CDC, US DHHS & NIOSH. Criteria for a recommended standard: occupational noise exposure revised criteria 1998. (1998). doi:DHHS (NIOSH) Publication No. 98–126

49. Zhao, Y.-M. et al. Application of the kurtosis statistic to the evaluation of the risk of hearing loss in workers exposed to high-level complex noise. Ear Hear. 31, 527–32 (2010).

50. Seixas, N., Neitzel, R., Sheppard, L. & Goldman, B. Alternative metrics for noise exposure among construction workers. Ann. Occup. Hyg. 49, 493–502 (2005).

51. Masterson, E. A., Themann, C. L., Luckhaupt, S. E., Li, J. & Calvert, G. M. Hearing difficulty and tinnitus among U.S. workers and non-workers in 2007. Am. J. Ind. Med. 59, 290–300 (2016).

52. Estill, C. F., Rice, C. H., Morata, T. & Bhattacharya, A. Noise and neurotoxic chemical exposure relationship to workplace traumatic injuries: A review ☆. (2016). doi:10.1016/j.jsr.2016.11.005

53. Santana, V. S. & Loomis, D. Informal jobs and non-fatal occupational injuries. Ann. Occup. Hyg. 48, 147–157 (2004).

54. Sorock, G. S., Lombardi, D. A., Courtney, T. K., Cotnam, J. P. & Mittleman, M. A. Epidemiology of occupational acute traumatic hand injuries: A literature review. Saf. Sci. 38, 241–256 (2001).

55. Khanzode, V. V., Maiti, J. & Ray, P. K. Occupational injury and accident research: A comprehensive review. Saf. Sci. 50, 1355–1367 (2012).

56. Amuzu, D. Unravelling Urban Environmental (In) justice of E-waste Processing Activities in Agbogbloshie , Accra-Ghana MPhil in Development Studies , Specializing in Geography. (2015).

57. Widanarko, B. et al. Prevalence of musculoskeletal symptoms in relation to gender, age, and occupational/industrial group. Int. J. Ind. Ergon. 41, 561–572 (2011).

58. Agwu, M. O. & Ajayi, S. O. Good Housekeeping - A Panacea for Slips, Trips & Falls Accident in the NLNG Project, Bonny. Int. J. Bus. Adm. 5, 12–20 (2014).

59. Tang, X., Hashmi, M. Z., Long, D., Chen, L. & Khan, M. I. Influence of heavy metals and PCBs pollution on the enzyme activity and microbial community of paddy soils around an e-waste recycling workshop. Int. J. Environ. Res. Public Health 11, 3118–3131 (2014).

60. Spellman, R. & Bieber, R. M. Physical hazards and controls. in Physical hazard control: preventing injuries in the workplace 1–7 (Government Institutes, 2011).

61. Munnzel, T., Gori, T., Babisch, W. & Basner, M. Cardiovascular effects of environmental noise exposure. European Heart Journal (2014). doi:10.1093/eurheartj/ehu030

62. van Kempen, E. et al. The association between noise exposure and blood pressure and ischemic heart disease: A meta-analysis. Environ. Health Perspect. 110, 307–317 (2002).

Chapter 4 : Material Recovery, Income, and Avoided Emissions from Informal E-waste Recycling in a Thai Community

Chapter 4 Abstract

Introduction: Recovery and recycling of materials found in e-waste is an informal work sector that is growing in low-income areas across the globe. The informal sector is often cited as polluting humans and the environment; however, there is potential for the informal sector to produce environmental benefit in the form of avoided emissions. The informal sector may be more efficient in the collection of e-waste and recovery of materials, and additionally relies mostly on manual labor, reducing electricity consumption in the process.

Methods: Four e-waste products (washing machine, refrigerator, Cathode Ray Tube (CRT) television, and fan) were selected for use in a combined Material Flow Analysis (MFA) and Life Cycle Assessment (LCA). Data collection took place in an informal e-waste recycling community in Thailand where the materials recovered for each product were recorded along with the product flow data for one village. These results were fed into a LCA to calculate the avoided emissions and damages (in terms of human health, ecosystem quality, global warming, and resource use) per material type, per product and for the entire community.

Results: Recyclers recovered approximately 93% or better of the original mass of the product. The village recycled nearly 40,000 kg of e-waste comprised of these four product types per month, with an associated net value added of 157,000 THB. The net avoided human health damages are 0.2 DALYs. Additionally, nearly 60,000 kg CO_2 equivalents are avoided in climate

change impacts and nearly 400,000 MJ are avoided in resource damages. The community sustains approximately 3 million Potentially Disappeared Fraction*m2*yr in ecosystem damages each month, largely due to lead from landfilled CRT screens. This will be offset when comparing e-waste recovery with landfilling.

Conclusions: Informal e-waste recycling appears to have net benefits in terms of avoided emissions with the exception of improper handling and disposal of hazardous materials, such as leaded CRT screens. In addition, informal recycling is showed to be relatively efficient in recovery of materials and economically beneficial to communities who engage in recycling activities.

4.1 Introduction

4.1.1 E-waste and end of life scenarios

By the year 2020, it is estimated that the world will produce more than 50 megatons of e-waste per year [1]. Electronics that have reached the end of their use phase will eventually enter one of three main end-of-life (EOL) scenarios: repair, landfill, or recycling [2]. An overview of the life cycle and main EOL scenarios of e-waste is shown in Figure 4-1. The generation of e-waste has outpaced solutions to process the growing waste stream, including formalized recycling systems [3]-[5]. This deficiency of technology and infrastructure, combined with a lack of regulatory and economic incentives in many countries, results in hoarding and/or improper disposal of e-waste products by consumers [6], [7]. E-waste globally is the fastest growing waste stream, and though estimates vary depending on country and region, a portion of e-waste ends up in landfills in every country each year [1]. An estimated 1.3 million tons of e-waste was disposed of in landfills in the United States in 2014 [8]. Landfilled e-waste results in a loss of their valuable materials, including copper, steel, gold, rare earth elements, and some plastics, that could have potentially been recycled and reused [9]. Repaired electronics can also re-enter the use phase, extending the life cycle of the product.

EOL processes are different between formal and informal recycling. Part of the e-waste that enters the informal recycling stream is repaired rather than recycled, or parts are kept during the recycling process to use in future repairs [10]. This repair process is less frequent in formal recycling, due to additional complications associated with legal considerations regarding company contracts and data security [11]. Informal e-waste collectors in some areas of the globe sort through waste streams to recover disposed electronics and divert them into the e-waste recycling or repair stream [10], [12]. Both formal and informal recycling yield waste products that cannot be recycled, such as certain plastics, small concentrations of rare metals, and coated glass, which are landfilled [13], [14].

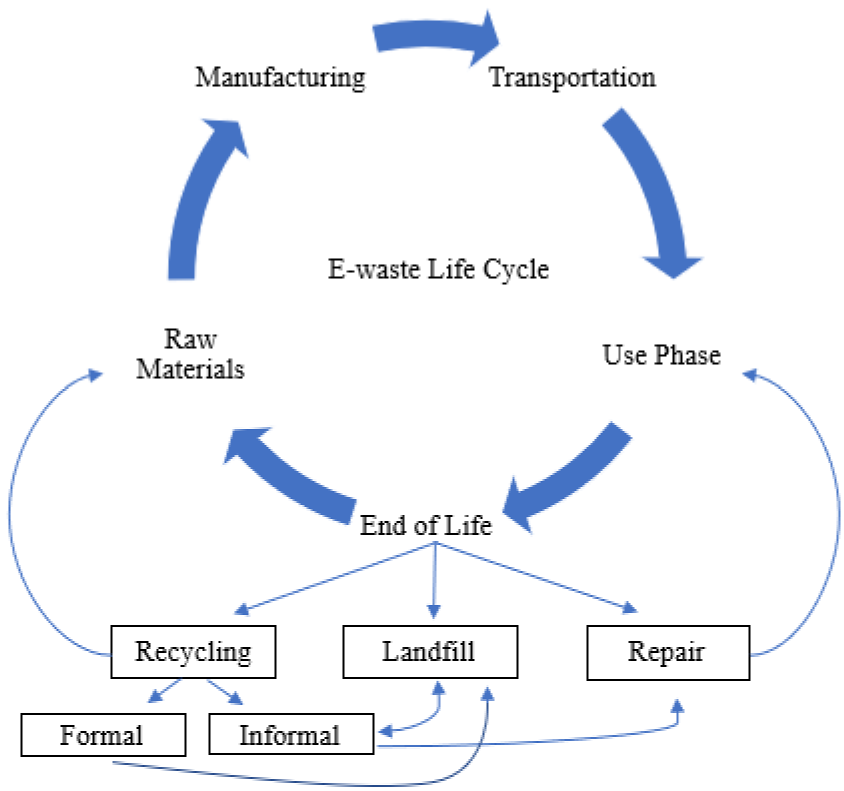


Figure 4-1 Life cycle of electronic waste showing three end-of-life scenario and the relationship between informal recycling and other life stages of products.

4.1.2 Comparison between formal and Informal e-waste recycling

There is no definitive definition of what constitutes informal e-waste recycling; however, as in other informal industries, it is generally associated with a lack of regulation and infrastructure [15]. As a result of lax oversight and inadequate resources, informal e-waste recycling often coincides with contamination of local environments, workers, and communities [16]-[22]. Informal e-waste workers employ dangerous methods in the recovery of recyclable materials, including the burning of copper wires and improper handling and disposal of CRT glass [12], [23]-[25]. Informal e-waste recycling sites are expected to increase in number throughout the developing world as the quantity of e-waste generated globally increases, resulting in an increase in pollution [1], [26], [27].

Some studies suggest that formalization of the informal e-waste recycling sector could reduce the impacts caused by informal recycling by imposing and enforcing occupational and environmental health standards [1], [28]-[30]. Formalized recycling of e-waste can potentially reduce environmental contamination, worker and community exposures to hazardous chemicals, and offers recuperation of valuable materials, reducing demand for virgin materials [31]. However, while formal recycling might offer some protection through controls, workers in formal recycling facilities in the U.S. and in Sweden have also been shown to be exposed to e-waste chemicals [32]-[34]. Recycling of e-waste containing hazardous materials, including leaded glass, polybrominated diphenyl ethers (flame retardants), and chlorofluorocarbon (insulation foam), requires specialized techniques in controlled conditions to prevent these chemicals from entering the environment [35]. Similarly, specialized methods and economies of scale are needed to extract rare and trace elements from electronics [36]-[38]. Extraction of rare and trace elements involves the use of hazardous chemicals and creates a stream of hazardous waste that can be costly to dispose of appropriately [14], [37].

Despite the benefits offered by formalized recycling, informal e-waste recycling offers several important advantages compared to the formal sector. First, the formal sector does not currently have the capacity to handle the global e-waste stream, and so the informal sector is needed [1], [13]. In part, the lacking capacity of the formal sector is due to the high cost associated with formal recycling [39]. Until formal recycling becomes a prevalent and affordable option, informal recycling offers recovery of materials that would otherwise be landfilled. The informal sector therefore provides environmental and economic benefits by reducing the demand for mining of virgin materials [31], [40]. Secondly, informal recycling can be more efficient in some tasks, such as the collection of e-waste from waste streams, sorting of e-waste products, and recovery of materials during preliminary dismantling activities [30], [39], [41], [42]. For example, e-waste streams are heterogenous in their composition of products, and individual categories of products are variable in their material composition with differences between brands, models, years, and geographic locations [13], [43]. To deal with this complexity, the formal sector is forced to develop expensive technology to sort e-waste into similar materials. The informal sector relies on lower-cost manual sorting and disassembly, sometimes resulting in higher recovery yields [44]. Finally, repair and reuse of e-waste products and parts is common in the informal sector, reducing the demand for new products and parts [25], [45], [46].

4.1.3 Valuable materials and economics of e-waste recycling

The value of secondary raw materials contained in e-waste was estimated at approximately 63 billion USD in 2017 [7]. Valuable materials and components, including copper, ferrous metals, aluminum, and printed circuit boards (PBCs), can be recovered from e-waste and sold to generate income. The value of individual e-waste products is determined by the concentration of valuable materials inside, the ability of workers to recover those materials, and market prices for raw secondary materials [31]. Additionally, costs are saved in the reduced need to extract virgin materials and the avoided processing steps of primary materials in the form of energy savings [47], [48]. While some information exists on the income generated by formal recycling companies in countries like Sweden, little information exists on the income for e-waste workers in the informal sector.

The informal e-waste recycling sector serves as an important source of employment for a large number of low-skilled workers across the globe [49]-[51]. For example, in Ghana, an estimated 0.5% to 0.8% of the total population is employed in the informal e-waste sector [52]. In Guiyu, China, 80% of the city's residents are employed in e-waste recycling [53]. In India, an estimated 85,000 workers are employed in the informal e-waste sector in the capital city of Delhi alone [54]. Informal recycling provides an important source of employment in Thailand, too, though no official estimates of size of the sector exist. As China has gradually increased regulations and enforcements on e-waste recycling, Thailand has become a major dumping ground for e-waste [55]. Therefore, the expected trend of poor and marginalized populations seeking employment in the sector [56] will likely continue in Thailand as the e-waste stream grows.

Despite the importance of e-waste as an income for populations across the globe, little is known about the earnings of informal workers. Studies from Ghana report that the income of e-waste workers to be higher than the daily minimum wage [57], [58]. Other studies, like one from Pakistan, merely comment on the importance of e-waste as an income [59]. A more comprehensive assessment on the income of e-waste workers, including the income generated on individual products, is required for consideration in conjunction with environmental and human health effects to inform decision makers on best practices for e-waste policy and interventions.

4.1.4 Material flow and environmental life cycle assessment of e-waste

Material flow analysis (MFA) is an analytical method than can be used to measure the flows of products or materials through a defined system [60]. The tracking of informal and illegal e-waste is difficult due to multiple endpoints, lack of organization and systems to track products, etc. [61]. Therefore, there is a dearth of studies on the flow of materials in the informal e-waste recycling sector. Available information on the flow of e-waste materials, as well as end-of-life recycling scenarios using life cycle assessments, are largely limited to formal sectors and middle- or high-income countries [62], [63]. Additionally, many studies have focused on the generation or collection of e-waste products but have failed to examine the flow of e-waste materials from the product to the secondary raw material stage [25], [28], [64], [65]. The few studies that have examined these issues in the informal sector often have not relied on primary data, but rather a conglomeration of estimates [10], [66], [67]. Some materials are not recovered from e-waste during formal and informal recycling due to factors including worker behaviors, available tools and techniques, and material recycling technology limitations [68]. In the informal sector, decisions and recovery rates are possibly influenced by other factors, including market prices of products and materials as well as manual dismantling abilities. Detailed data from informal recycling operations is needed to estimate the performance of the informal sector's ability to recover material compared with the formal sector, as well as to estimate the flows of products and materials in e-waste communities.

Life cycle assessment (LCA) is a decision-making tool that characterizes the entire life cycle of a product or process [69]. LCA methods can be applied to EOL processes for a product, allowing for the comparison of each process in the treatment of waste. Although some studies have shown that the EOL does not have the dominant environmental impacts for some electronics [70]-[72]. LCAs focusing on EOL treatment options of e-waste have shown positive environmental benefits in formal recycling facilities compared to other EOL scenarios [62], [63], [71], [73], [74]. Existing LCA literature focuses on impacts of recycling in the formal sector, excluding differences in techniques, processes, and inputs found in the informal sector [75], [76].

This exclusion in the informal sector is important because processes like the burning of e-waste and improper disposal of e-waste is likely to have additional important impact, whereas avoided environmental impacts associated with the EOL of e-waste in informal recycling are unknown and a main source of uncertainty. More information is therefore needed to address the environmental and human hazards associated with informal e-waste recycling.

4.1.5 Research objectives

The overall aim of this study was therefore to consistently and comprehensively assess the material flow, economic performance, and environmental damages due to operations in an informal e-waste recycling community in Northeastern Thailand. The first objective was to determine the material recovery efficiency and economic impact of e-waste recycling at the product- and community-level using MFA and economic analyses. The second objective was to determine the environmental impact of informal e-waste recycling at the product- and community-level using life cycle impact assessment (LCIA) methods for the EOL product phase. Together, this information will help inform decision-makers on which products and materials have the largest economic impact, as well as which will have the largest environmental impacts. Both aspects are important when considering how to improve the environmental health aspects of informal recycling as well as preserving this important source of employment for workers.

4.2 Methods

4.2.1 Study site, participants, and product selection

Data for this study were collected from four neighborhoods in a larger e-waste recycling community near the city of Kalasin, in Northeast Thailand. This community was selected for several reasons, including the recovery and recycling of most types of materials. Unlike recyclers in other areas, such as Chile, recyclers in Thailand recover and recycle nearly all materials from e-waste, including plastics. Additionally, recyclers were observed to recycle using relatively similar methods, which allowed for an assumption of similar recovery rates between recyclers. Participants were selected with the assistance of local community health workers and local researchers using convenience sampling methods. The study methods were approved of by the Institutional Review Board at the University of Michigan (HUM0014562) in the United States and at Mae Fah Luang University (REH-59104) in Thailand.

Four e-waste products were selected based on their relatively simple design in terms of numbers of materials and components as well as their abundance in the community. These four products were: washing machines, refrigerators, CRT televisions, and upright fans. One of the four villages, “Village 4”, was selected for additional surveys of all e-waste recycling households within that neighborhood.

4.2.2 Material recovery and economic data collection

This study employs a combined MFA and LCA approach. The boundaries for the MFA were set on the physical and process boundaries in Village 4. Materials recovered from each of the four selected products were obtained in the field while workers were actively recycling items (See Appendix D). Masses of individual products were first recorded in the field – along with the mass of each type of material, including waste, recovered from the individual products – using a digital food scale for smaller items and a large analog scale for heavier items. A mass balance was run on each product as data quality check to ensure accuracy of measurements (See Appendix D). Products with incomplete mass records or with invalid mass balances were removed from the data set. Materials were categorized by workers who knew from experience the difference between metal composition in different products and subassemblies.

The flow of the selected four e-waste product types was collected from all known households in Village 4 that engaged in e-waste recycling activities through in-person surveys. The average number of each product type recycled per month was calculated, along with the average number of products recycled per month for all of Village 4. These results were then multiplied by the material recovery data from individual products to complete our material flow at community level.

Workers provided economic data for the products. Information was collected on the purchase price for each electronic product for which mass data was collected. In addition, workers provided the current market price for different material types. Finally, additional overhead costs, including labor, electricity use, and out-sourcing of processes were considered. Cost of tools was not included. The net value added was then calculated by combining the product specific material flows with purchase and material prices. An economic balance was run for each observation as a data quality check.

4.2.3 Life Cycle Assessment

An LCA study was conducted using the per product and community MFA results and combining it with Life Cycle Assessment data of material production and recycling to estimate the net impacts of informal e-waste recycling, focusing on EOL processes and related raw material substitution. The informal recycling scenario was compared to the entire landfilling of e-waste as baseline scenario to derive a net benefit or impact; The landfilling of inert waste materials and CRT glass from the informal sector is the same in the baseline scenario, but the associated impacts were nevertheless estimated to also evaluate the entire impacts of informal recycling and discuss the further benefits that can be obtained by proper disposal of CRT glass with lead. The LCA was used to calculate the human health, ecosystem quality, climate change, and resource impacts for each product, related material type and associated processes. A normalization step was applied at the end to aid the interpretation of results [77], [78].

4.2.3.1 LCA goal, system boundaries and functional unit

The goal of this LCA was to quantify the environmental impacts of informal e-waste recycling for four products. The system boundaries for this analysis are shown in Figure 4-2. The e-waste recycling system begins when the e-waste enters the Thai community where it will be recycled and considers all processes up through the production of secondary materials. The boundary ends at a point where the processing of primary raw materials and secondary raw materials is comparable to compared with the mining of virgin materials. We did not consider transport to the community for the products due to the heterogeneity of origin. The e-waste recycling system is split between two major steps. The first step is the manual dismantling, sorting, and disposal of e-waste that occurs in the Thai community. The second step is the transportation and processing of recovered materials at facilities in Bangkok, Thailand. Data from the product specific MFA were used to inform the first step. The processes from second step were adapted from two main studies, i.e. a 2005 study by Hischier *et al*. and a 2011 study by Wager *et al.* on the Swiss e-waste recycling system [63], [79]. The net impacts are then calculated assuming a substitution of virgin material, and subtracting the emissions, extractions and impacts associated with the production of primary virgin materials. The recovery scenario is then qualitatively compared with a baseline scenario of landfilling of the products. For each of the four selected e-waste products. The functional unit (FU) was one product unit recycled in the informal sector.

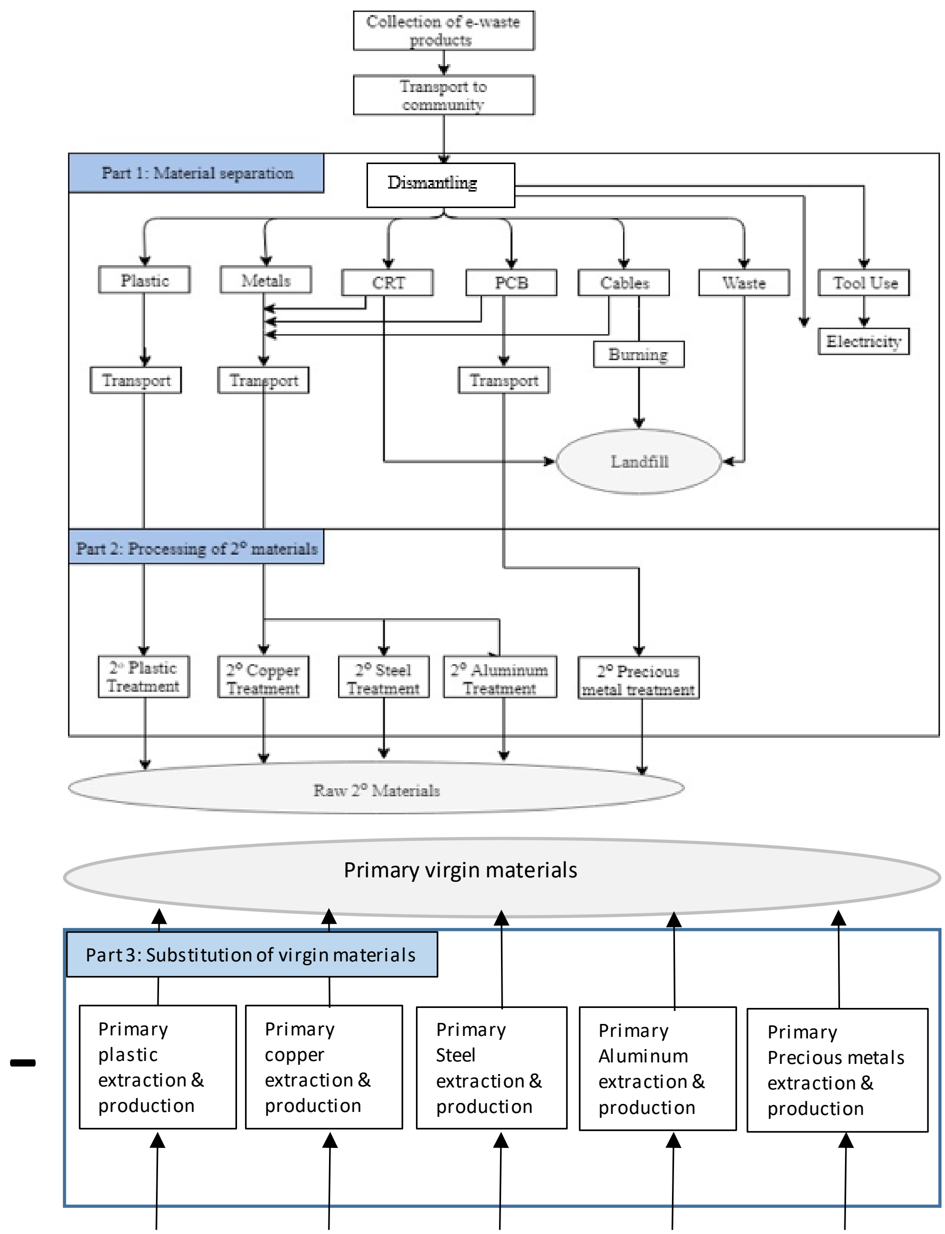


Figure 4-2 System boundaries of the e-waste in the modeled informal e-waste system, including steps occurring between the arrival of e-waste in the community through the production of secondary materials.

4.2.3.2 Inventory data and LCIA

For each product, the starting mass and the mass of all recovered materials were taken as the average value from all included MFA data for that product type. Tool use was added to each product type for three commonly used tools: hammer, pliers, and electric drill (See Appendix F, Section F-1). All three tools were modelled in the inventory database and then integrated in the process flow of each of the four product types. The quantity of each tool added per product was calculated based on the estimated average lifetime of a tool (based on conversations with participants) and the number of products recycled during that lifetime (based on village 4 product flow results). Duration of use of the electric drill was estimated for each product based on field observations and video recordings of several participants (see Chapter 3) and multiplied by measured power usage to provide the drill electricity consumption (kWh) per FU.

All inventory processes are shown in Appendix E. To model copper recovery from burning of cables, a collection of e-waste cables from different products in the Thai community were collected and stripped to determine the mass of the copper without coating. An additional percentage loss from vaporization of copper during burning was calculated based on experiments characterizing e-waste burning by Gullet *et al.*, 007 [80]. Air Emission factors per kg cable burned were also taken from this same paper. Copper recovered from cables was treated the same as copper recovered from other e-waste components.

Processes in secondary material treatment (part 2 of Figure 4-2) were characterized using existing and modified data in the Life Cycle Inventory (LCI) database Ecoinvent v3.5 [81]. *Table 4-1* summarizes the major assumptions made for different processes in the LCA, whereas additional assumptions and processes are shown in Appendix D. For transport to the secondary processing facilities, a distance of 520 km was used as the distance between the e-waste study site and Bangkok. Printed circuit boards (PCBs) were modeled using a cascade of treatments to recover copper, gold, silver, and palladium. To model the informal e-waste recycling scenario comparison with the complete landfilling of e-waste products, avoided emissions are calculated by subtracting the emissions associated with virgin mining of materials from the processes required to transform recovered scrap material from e-waste to raw secondary materials. Where possible, primary production processes were taken from the Rest of World (RoW) Ecoinvent datasets. If RoW was not available for a process flow, then Global (GLO) or the next best alternative was used. The cut-off unit process was selected from the Ecoinvent database for all applicable process flows.

Table 4-1 Assumptions and estimates for materials and processes in the LCIA.

Inventory item	**Author assumptions**
Metals recycling	• Transport to treatment plant 520 km, 3.5-7.5 metric ton lorry, EURO3. Thailand's current emission limits correspond better to EURO2 emission standards; therefore, emissions for CO and NOx were updated in process flow to reflect EURO2 standards [82]. • Ratios for inputs of secondary scrap metal to outputs of secondary raw materials were taken from methods on previous WEEE studies by Empa Technology & Society Laboratory experts of St. Gallen, Switzerland [63], [79]. • Processing of scrap metal modelled on technology available in Europe, early 2000s.
Plastic recycling	• Transport to treatment plant 520 km, 3.5-7.5 metric ton lorry, EURO3. • Electricity mixture: medium voltage, Thailand. • Process heat: Heat, central or small-scale, natural gas {GLO}. • Input of MBA polymers contain 11.5% of metals (Al, Cu, steel); results in 40% output of secondary polymers (ABS, PS, PP). Energy input, chemicals consumption, waste treatment parameters kept constant. • Scrap plastic processes modelled on technology available in one plastics recycling facility in Austrian the early 2000s. Plastics analysis performed by Dr. Roland Hischier of Empa Technology & Society Laboratory experts of St. Gallen, Switzerland; process is confidential data until 2022. • Avoided plastics were assumed to be 42% ABS, 28% PS, 20% PP based on Stenvall *et al*., 2013 [83].
PCB recycling	• Separation and shredding of PCBs and cascade process to remove Au, Ag, and Pd from circuit boards modelled based on methods used in Europe. • Only Au, Ag, Pd, and Cu recovery from PCB considered. Remaining materials treated as inert landfill waste.
CRT glass	• Pb concentration in CRT glass calculated based on Mear et al, 2006: 33% of CRT glass is leaded; 25% of leaded glass is PbO by mass [84]. • Assume 100% of Pb will leach from CRT glass (including long-term) to soil.
Cable burning	• Assume 67.5% copper recover (by cable mass) based on plastic coating striping experiments by author (-28%) and loss of copper to vaporization from combustion experiments (-4.5%) by Gullet *et al*., 2007 [80]. • Emissions to air from combustion based on findings from Gullet *et al*., 2007 [80].
Waste	• Waste that was recovered was modelled as inert landfill waste.

Uncertainty was estimated using the Pedigree Approach assuming lognormal distributions [85]. Geometric standard deviations were calculated using data quality indicators and default uncertainty factors as detailed in Jolliet *et al.*, 2016 [86]. For the uncertainty on the material mass decomposition from the MFA, a normal distribution was assumed, and standard deviations calculated from field data.

4.2.3.3 Impact assessment methods and normalization

Two LCIA methods were selected as results between methods are known to vary in some cases [87]-[89]. The impact assessment was performed using the Impact 2002+ methods [78], [87] run by the SimaPro PhD software. A sensitivity analysis was also performed with the Hierarchist scenario of ReCiPe 2016 v1.1 midpoint and endpoint method [88] (Appendix G) covering a wide range of impact categories [89]. Similarities and differences in endpoint damage and endpoint characterization categories are shown for each method in Table 4-2. Damages were calculated for each method and reported for each material type (impact per kg recovered e-waste material) and by product (impact per product). Finally, monthly neighborhood impacts and benefits were calculated using the overall mass flows of each product type treated in Village 4 .

Human health endpoint damage categories were reported in disability-adjusted life years (DALYs) and represent the number of years of life lost due to mortality and morbidity over the entire population [90]. The ecosystem quality damage category has the unit PDF*m^2*year and represents the "potentially disappeared fraction" (PDF) of species over a certain area (1 m^2) during a year [87]. Climate change is given in unit of kg CO_2 equivalents (CO_2 eq) to characterize the cumulative effect of greenhouse gases. Finally, the resources damage impact category is reported in megajoules (MJ) and represents the amount of energy extracted, or the amount of energy needed to extract a resource [87]. Units for endpoint damage characterization used in IMPACT2002+ methods are further detailed in the Impact 2002+ User Guide by Humbert *et al*., 2012 [87].

Table 4-2 Comparison of endpoint damage categories and endpoint damage characterization categories for Impact 2002+ and ReCiPe 2016 LCIA methods.

	Impact 2002+ Category		**ReCiPe 2016 Category**	
	Endpoint damage categories	**Unit**	**Endpoint damage categories**	**Unit**
	Human health	DALY	Human health	DALY
	Ecosystem quality	PDF*m^2*yr	Ecosystem quality	species.yr
	Climate change	kgCO_2 eq.	N/A	N/A
	Resources	MJ primary	Resources	USD 2013
	Endpoint characterization categories	Unit	Endpoint characterization categories	Unit
Human health	Carcinogens	kg C_2H_3Cl eq	Human carcinogens	kg 1,4-DCB
Human health	Non-carcinogens	kg C_2H_3Cl eq	Human non-carcinogens	kg 1,4-DCB
Human health	Respiratory inorganics	kg $PM_{2.5}$ eq	Fine particulate matter formation	$PM_{2.5}$ eq
Human health	Ionizing radiation	Bq C-14 eq	Ionizing radiation	kB1 Co-60 eq
Human health	Ozone layer depletion	kg CFC-11 eq	Ozone depletion	kg CFC-11 eq
Human health	Respiratory organics	kg C2H4 eq		
Human health			Ozone formation	kg NOx eq
Human health			Global warming, human health	kg CO_2 eq
Ecosystem quality	Aquatic ecotoxicity	kg TEG water	Freshwater ecotoxicity	kg 1,4-DCB
Ecosystem quality			Marine ecotoxicity	kg 1,4-DCB
Ecosystem quality	Terrestrial ecotoxicity	kg TEG soil	Terrestrial ecotoxicity	kg 1,4-DCB
Ecosystem quality	Terrestrial acidification	kg SO_2 eq	Terrestrial acidification	kg SO_2 eq
Ecosystem quality	Land occupation	m^2 org.arable	Land use	m^{2}a crop eq
Ecosystem quality	Aquatic acidification	kg SO_2 eq		
Ecosystem quality	Aquatic eutrophication	kg PO_4 P-lim		
Ecosystem quality	Global warming	kg CO2 eq	Global warming*	kg CO2 eq
Ecosystem quality			Water consumption*	m^3
Resources	Non-renewable energy	MJ primary		
Resources	Mineral extraction	MJ surplus		
Resources			Mineral resource scarcity	kg Cu eq
Resources			Fossil resource scarcity	kg oil eq

*Also contributes to human health endpoint category.

A normalization step was applied to the IMPACT 2002+ results. Normalization allows for comparison between impact categories by converting them to relative contributions of the product to average global impacts [77]. Rather than provide damage category specific results, it allows for relative comparisons of impacts per functional unit to the total effect on a global scale for a given category [78].

4.3 Results

4.3.1 Mass flow analysis and material recovery

The total number of observed and included products for each of the four selected types of e-waste to be used in the material flow analysis is shown in Table 4-3. Products for which the recovery of all materials was higher than 80% of the initial weight were included. Average masses for each of the four products ranged from 2.7 kg for fan up to 32.3 kg for refrigerators.

Table 4-3 Product sample sizes and starting masses for the four e-waste product types considered in the mass flow analysis.

Product	**Washing machine**	**Refrigerator**	**CRT television**	**Upright fan**
Total observed	8	7	8	8
Total included	6	5	5	4
Mean (SD) (kg)	18.3 (2.4)	32 .3 (3.4)	21.5 (1.8)	2.7 (0.4)

Figures 4-3 through 4-6 are material recovery diagrams displaying the mean recovered masses of the four different e-waste products, along with the standard deviation. Additionally shown are the masses of some sub-components, including the mass of the CRT and compressor. The mass of recovered waste is shown, however the mass of any unrecovered mass, that is the mass of materials lost to the surrounding environment, was not measured. The pictures shown are from the field and represent the sources and components of the various material types for each product.

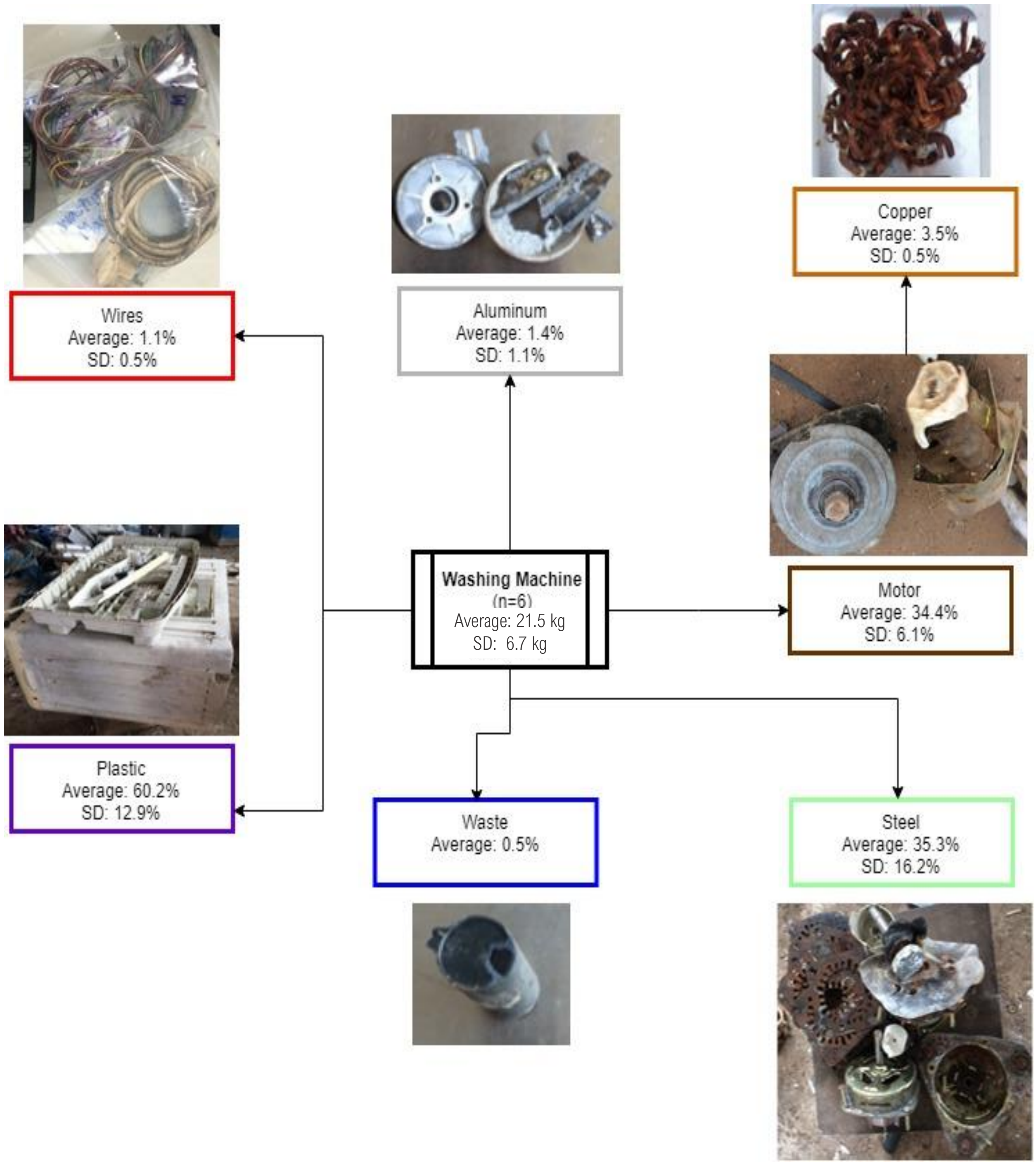


Figure 4-3 Average material composition by mass percentages for washing machines in research community in Thailand.

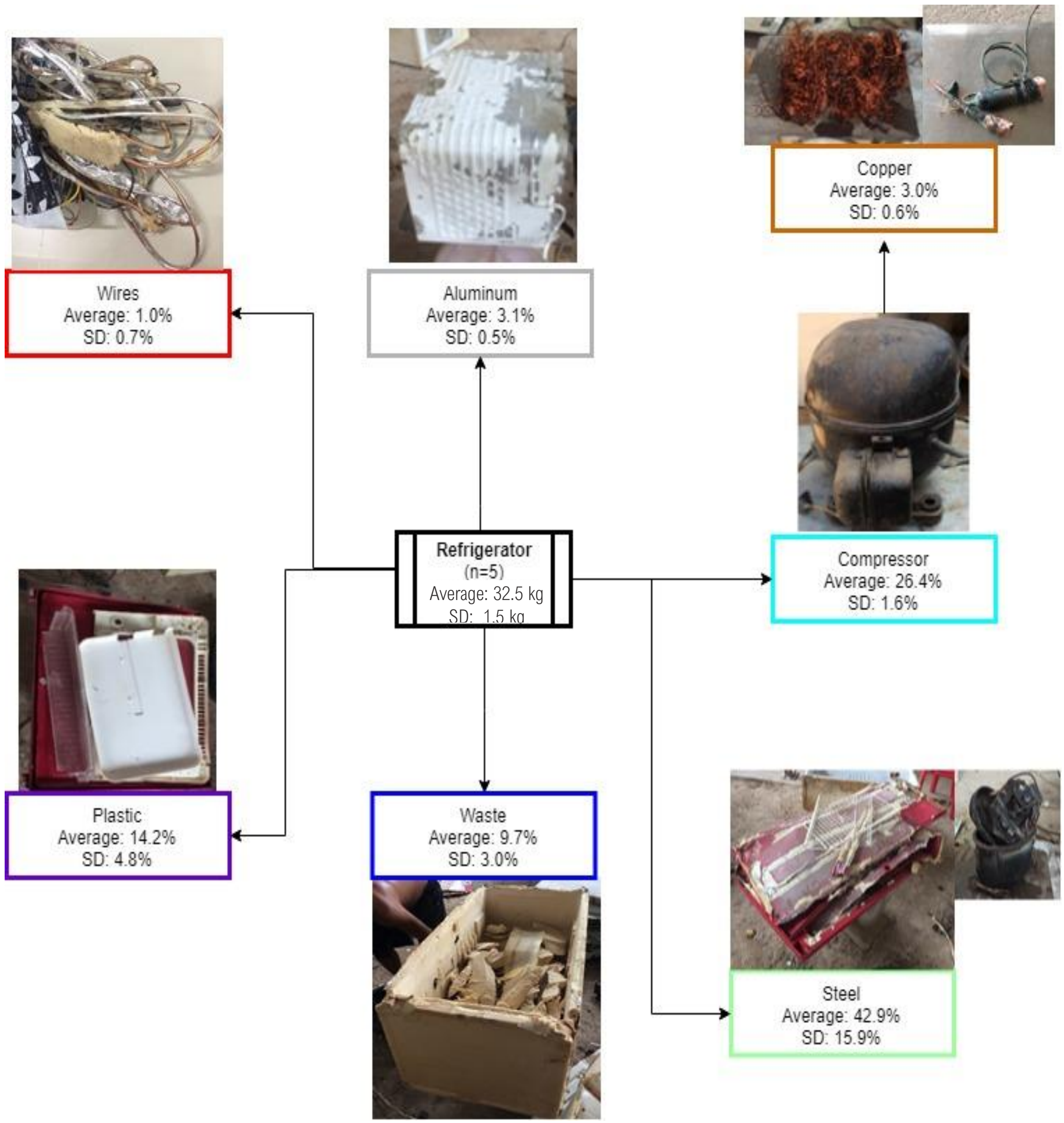


Figure 4-4 Average material composition by mass percentages for refrigerators in research community in Thailand.

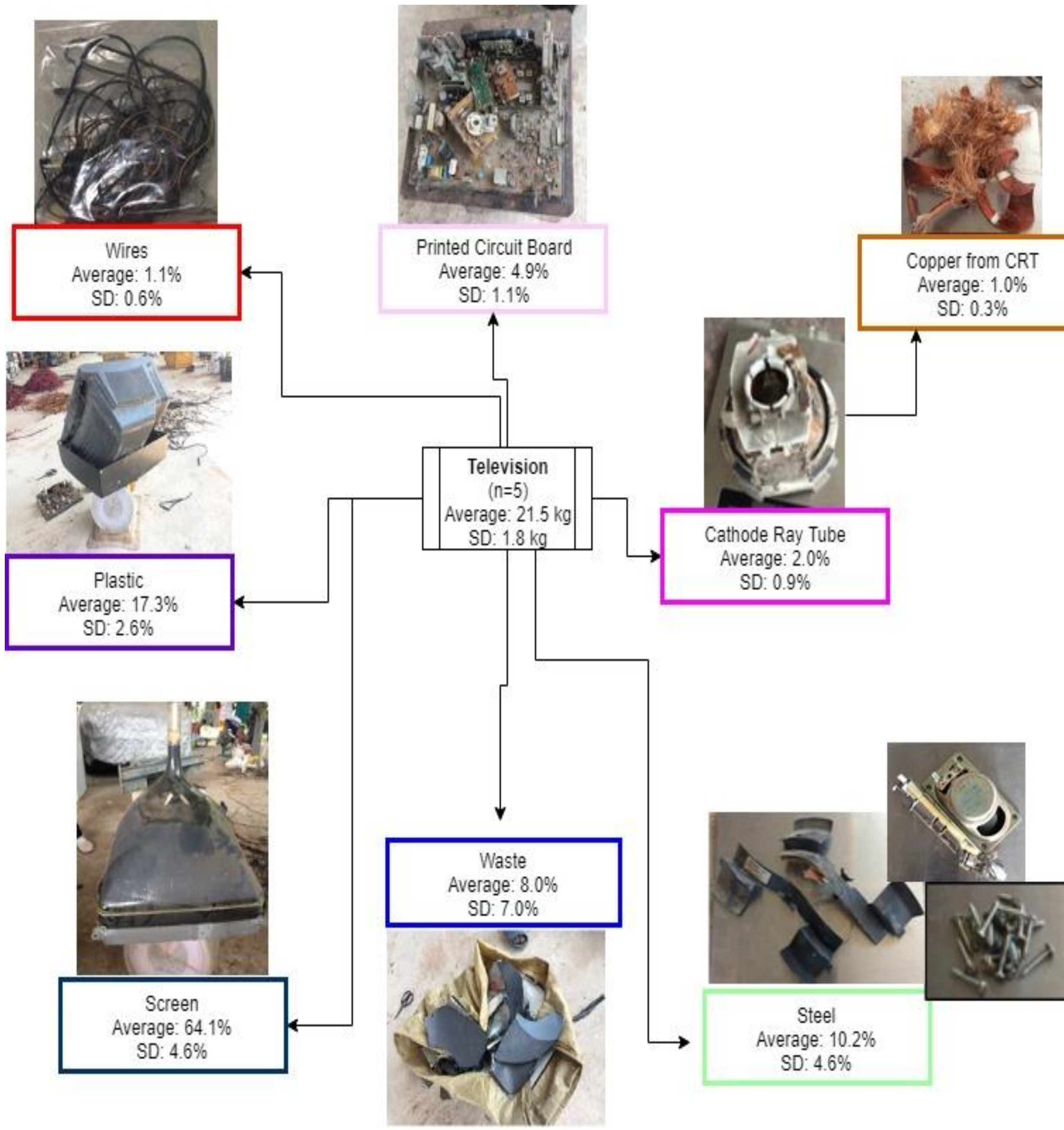


Figure 4-5 Average material composition by mass percentages for televisions in research community in Thailand.

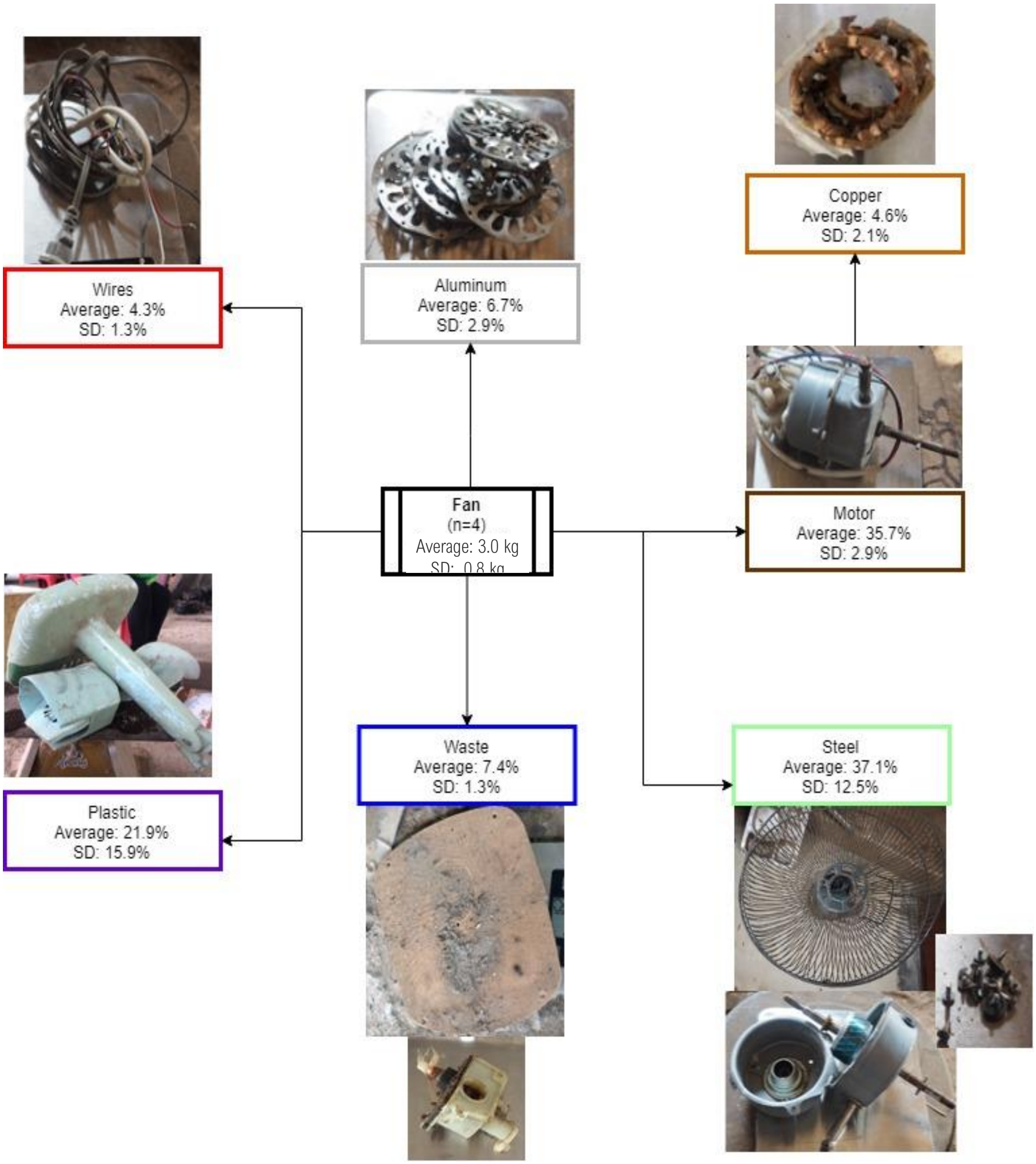


Figure 4-6 Average material composition by mass percentages for upright fans in research community in Thailand.

The material recovery from individual products are shown in Figure 4-7. Copper recovery after burning of cables was calculated to be 68.3% based on field tests and data in Gullet *et al.,* 2007 [80]. All products had a material recovery rate of approximately 93% or better by mass. Overall, televisions had the largest recovery rate based on mass; however, its recyclable recovery fraction is substantially lower when considering that the large mass of the CRT screen is landfilled. The difference in initial and recovered masses is due to loss of materials to surroundings. In some cases, e-waste workers may occasionally collect lost materials in their surroundings at irregular time intervals; however, this was not considered in our analysis since this is not a systematic practice. Refrigerators contain a foam lining that is not recyclable, resulting in the largest waste mass among the four product types after CRT units, which are mostly landfilled. E-waste recyclers in this community reported occasionally burning the foam lining to aid in the combustion of electronic cables; however, we did not include this occasional practice in our analysis. Overall, steel comprises the largest portion of the masses for fans, and refrigerators, whereas plastic represents the highest mass in washing machines. More than half the recovered mass of the television is CRT screen (64.1%, see Figure 4-5). The highest copper concentration was found in refrigerators, followed by washing machines. The only product with PCB materials was televisions (See Appendix D). Future e-waste products that have not previously contained PCB materials, including washing machines and refrigerators, may contain PCB materials in future waste streams as they are incorporated in “smart” technologies.

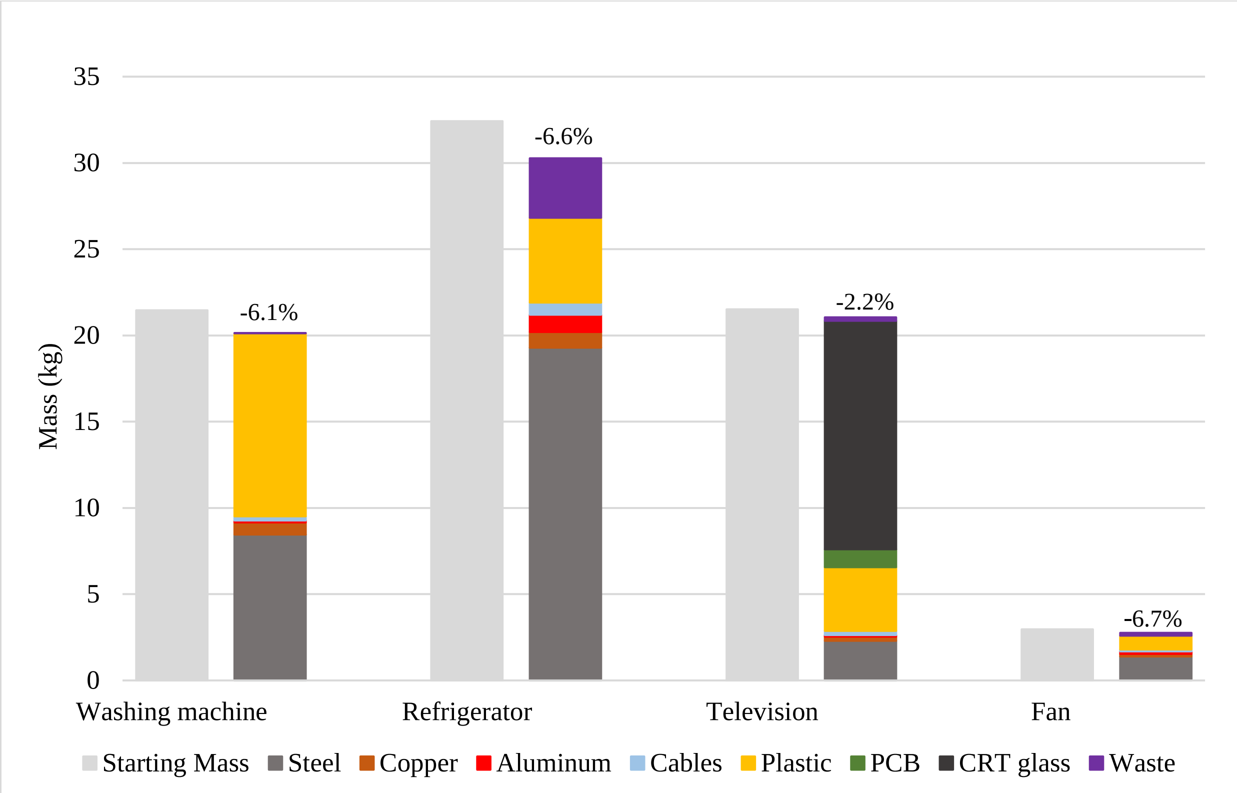


Figure 4-7 Quantities of materials recovered from informal recycling per piece of the four e-waste products.

The product flow in Village 4 is shown in Table 4-4. A total of 14 out of 165 households in Village 4 recycled e-waste products in 2017 according to government estimates (A. Arain, personal communication with field assistant and local government officials, July 2018). Table 4-4 summarizes the average number of products recycled per household month and the average number of products recycled per village per month by all 14 e-waste recycling households in village 4. The product with by far the most units recycled per month in Village 4 was fans (n=1185); roughly half as many televisions, refrigerators, and washing machines were recycled monthly (n=450-555).

Table 4-4 Product flow for four types of e-waste in one neighborhood of study site.

Product	Average/household/month	Average/neighborhood/month
Washing machine	32.1	450
Refrigerator	34.3	480
Television	32.5	555
Fan	84.6	1185

Multiplying the number of products recycled monthly by the material recovery quantities yield the recovered material amounts recovered by the Village 4 community for the four selected (Figure 4-8). Summing the four products, a total of 40,673 kg product is treated monthly, with 38,562 kg of materials or close to 95% recovered by informal e-waste against 2,111 kg or about 5% dispersed in the local environment. Of the recovered fraction, approximately 28,740 kg is recyclable material, excluding waste, CRT screens, and 32.5% plastic coating on cables. This implies that not all recovered materials are recyclable, and so a higher recovery rate does not necessarily equal a higher recycling rate. Despite having the highest quantity of products processed per month, the MFA shows that fans result in the smallest amount of materials due to the limited mass of each fan compared to the other products. Refrigerators again result in the highest lost waste, even when accounting for having the highest collective mass of all products. Once again, the foam lining likely accounts for much of the difference in the initial and recovered masses. Field observations revealed that the foam often broke and crumbled, and e-waste workers often left the foam where it lay.

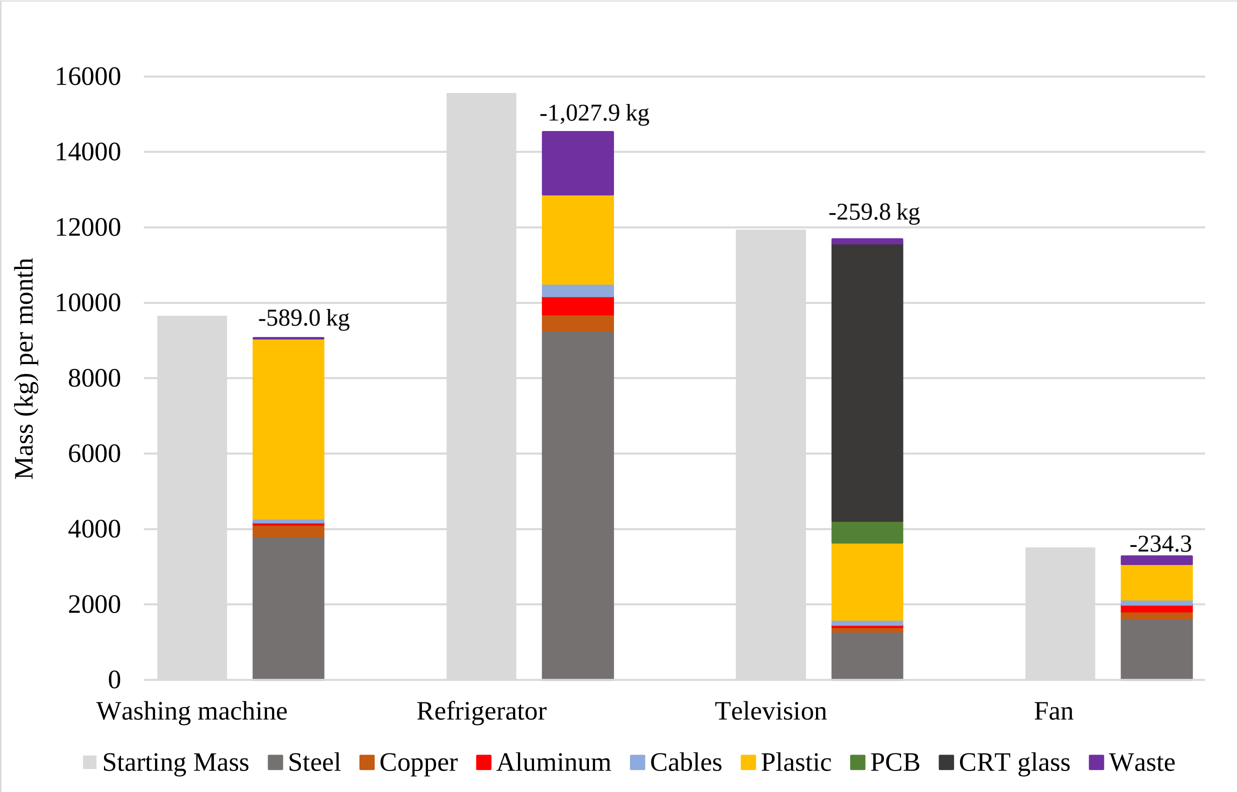


Figure 4-8 Monthly mass recovery by material type for four e-waste product types in one neighborhood in the study site in Thailand.

4.3.2 Economic analysis

The average scrap price (THB) per kg of recovered material from e-waste is given in Figure 4-9 for each material type. Recovered copper has the highest selling price of 175 THB ($5.30) per kg. Copper recovered from cables is sold at the same price, but must have the plastic PVC coating removed, usually by burning or striping the wires before being sold.

In addition to materials, CRT screens are sold for 10 THB per piece to other e-waste recyclers in the research site who break the glass and recover materials contained inside of the glass in the electron gun. The recycling of the electron gun was not considered in this economic analysis since it is outsourced outside of the community.

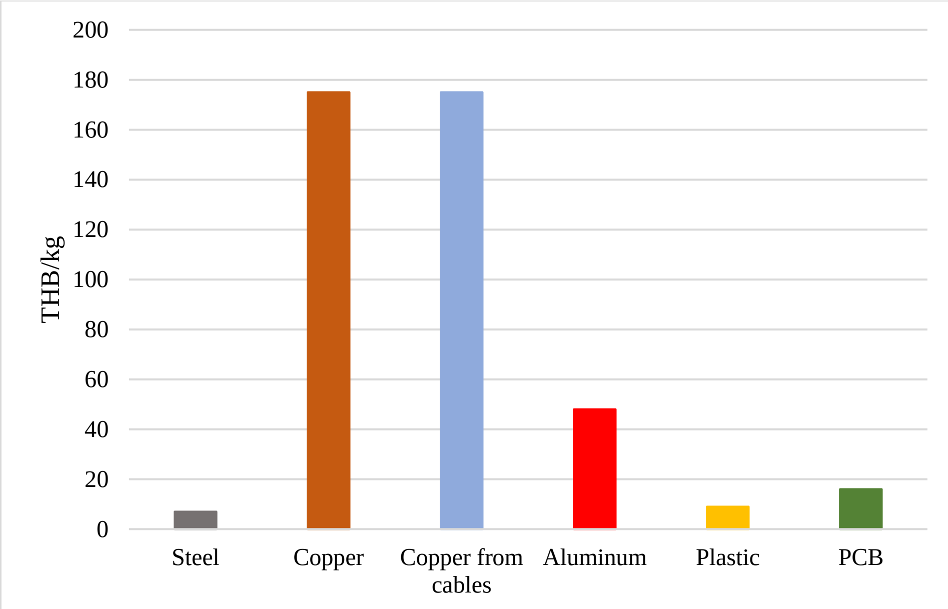
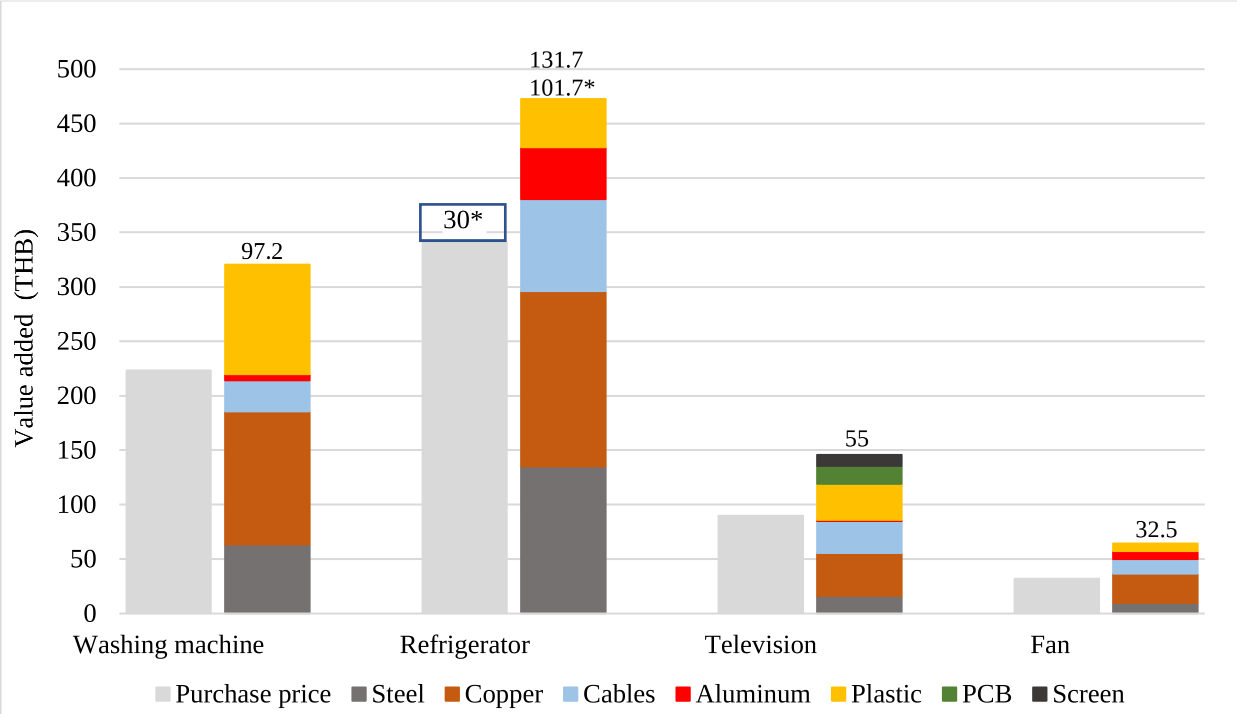


Figure 4-9 Sell price (in Thai Baht - THB) per kg of scrap material at research site during 2016-2017.

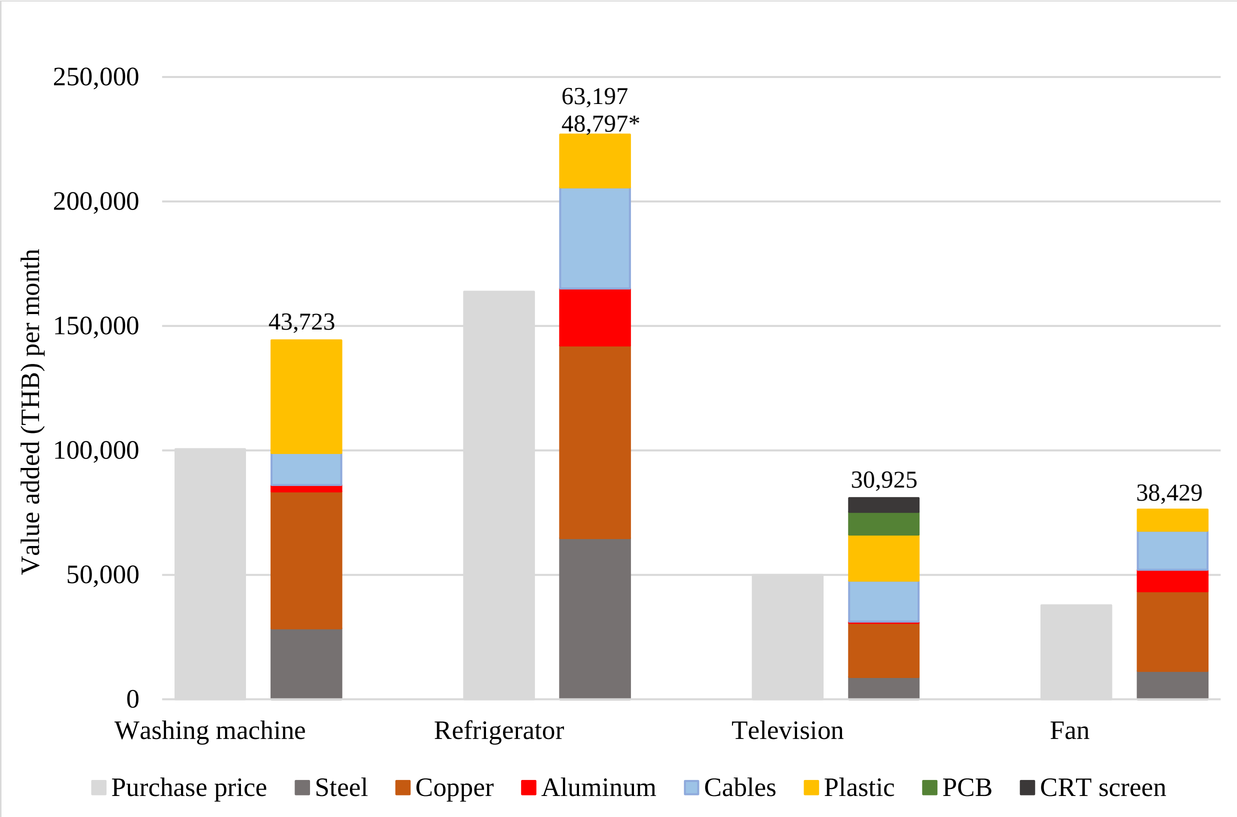
Figure 4-10 compares for each product the purchasing price with the cumulative revenue from the recovered recyclable materials, the difference between the two stacked bar representing the net value added per product type. Participating recyclers reported payment of 30 THB for the service of a welder to open the refrigerator compressor, which adds up to the refrigerator purchase price. The largest resulting value-added margin is in refrigerators at 101.7 THB per piece. Washing machines had a similar value added to refrigerators in the amount of 97.2 THB, while televisions (55.7 THB) and fans (32.5) were lower in absolute value, but higher proportionally to the purchase price.



*30 THB cost paid for welding services to open compressor in addition to purchase price.

Table 4-5 Purchase price for four e-waste products compared to total revenues associated with each recyclable material and product part recovered by informal methods in Thailand. Numbers of top of bars are the average net value added per product piece (THB/piece).

Figure 4-10 presents the combines the product flows from the MFA with the product-specific added values to yield the Village 4 added value at community level. Recycling of refrigerators in Village 4 results in a monthly value added of 48,800 THB per month. The combined value added for all four product types equals 157,100 THB (after welding costs). The minimum daily wage for a Thai worker in 300 THB. Assuming 22 working days per month, the value added by these four products alone in Village 4 generates enough income to pay for nearly 24 full-time minimum wage workers. The 14,400 THB paid to a welder each month to open the compressors would equal the equivalent of 48 days working minimum wage for the welder.



*30 THB cost to pay for welding services to open compressor.

Figure 4-10 Purchase price compared to total revenues associated with each recyclable material and product part recovered by informal methods in Thailand for one village during one month. Numbers on top of bars are the net value added per product type per month. "Cables" include the revenue from copper recovery from these cables. Numbers on top of the stacked column above refrigerator display the value added before and after costs to open the compressor.

4.3.3 Per material LCIA midpoint results

All results from the LCIA are given per kg of secondary material entering the recycling process. Results of the Impact 2002+ LCIA human health damage midpoint characterization per kg recovered material are displayed in Figure 4-11. Negative values indicate an avoided impact as a result of e-waste recycling compared to if the material had been landfilled. For respiratory inorganics and organics, ionizing radiation, and ozone layer depletion, PCBs had the largest avoided impacts per kg. In contrast, plastic had the largest net damage impact on ozone layer depletion, while steel had the largest net impact for ionizing radiation. Cables had the highest impact in the carcinogen and non-carcinogen impact categories due to the combustion emission of the plastic coating. Copper had the largest avoided benefit in the non-carcinogens category, while aluminum had the largest avoided value for carcinogens.

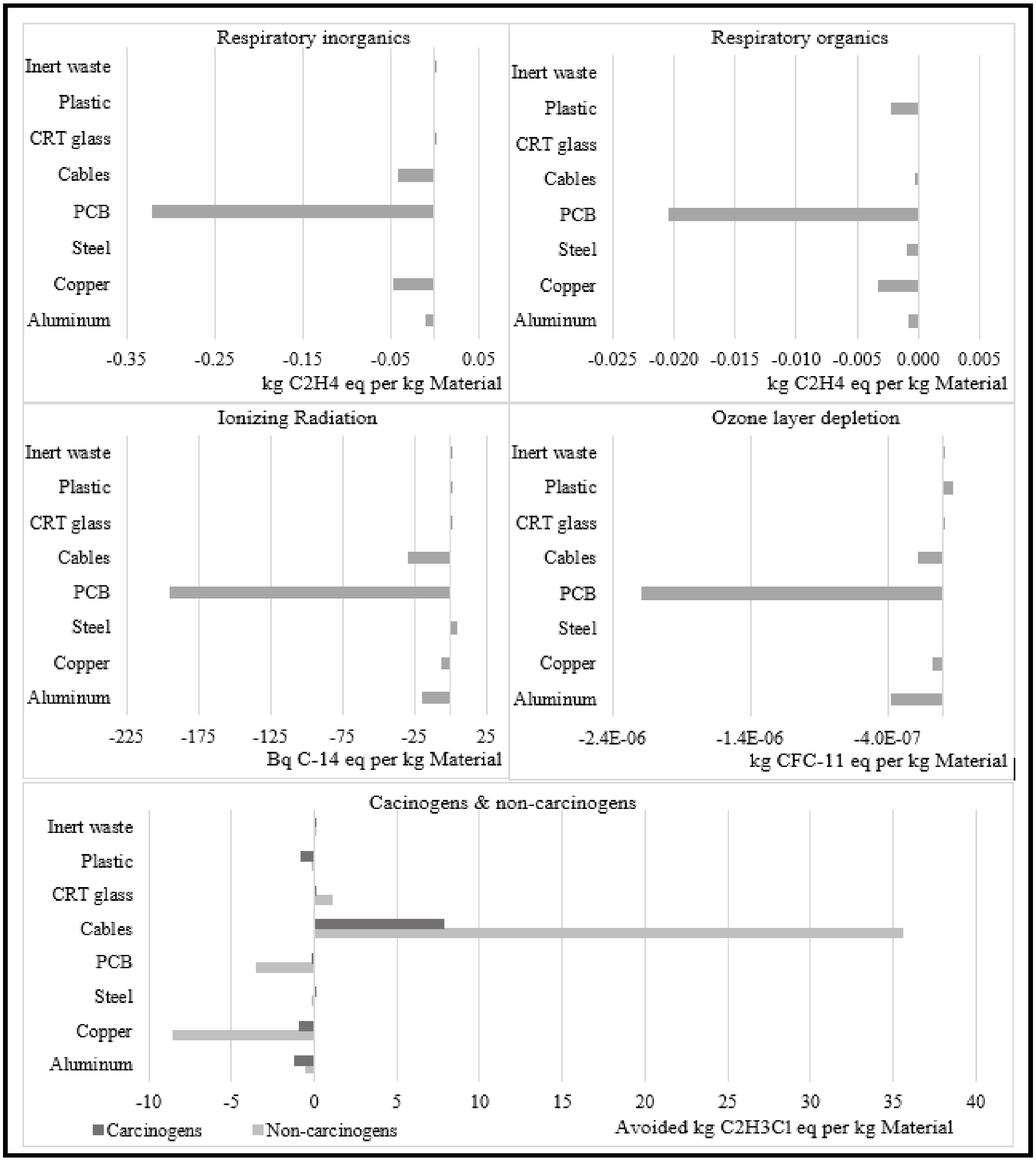


Figure 4-11 Human health midpoint impact characterization per kg material. "Cables" in this figure and in subsequent figures include the burning and the copper recovery from these cables.

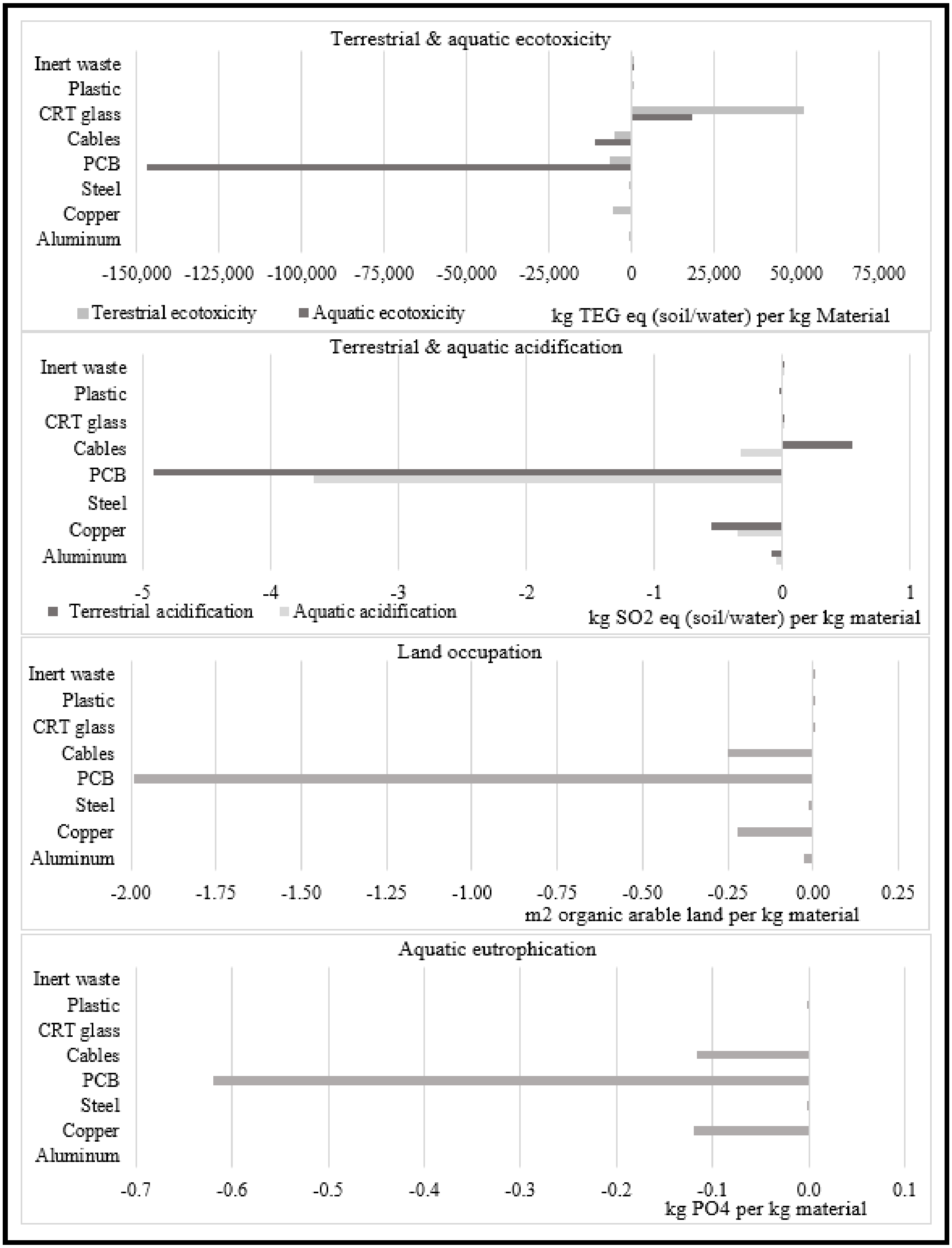


Figure 4-12 Ecosystem quality midpoint impact damage characterization per kg material.

Figure 4-12 shows the endpoint characterization per kg recovered material for ecosystem quality. For all categories, PCB has the largest avoided impact per kg material. CRT glass has the largest damaging impact for ecotoxicity (18,200.0 and 52,100.00 kg triethylene glycol (TEG) equivalents (eq), terrestrial and aquatic, respectively), but would be cancelled if the landfilling impact of the base scenario would be considered in a comparative assessment. Terrestrial acidification showed the highest per kg impact in cables (0.546 kg SO_2 eq), while plastic had the highest positive impact per kg for aquatic acidification (0.003 kg TEG eq). Results from CRT glass, inert waste, and plastic show positive comparable impacts in the land occupation and terrestrial ecotoxicity categories.

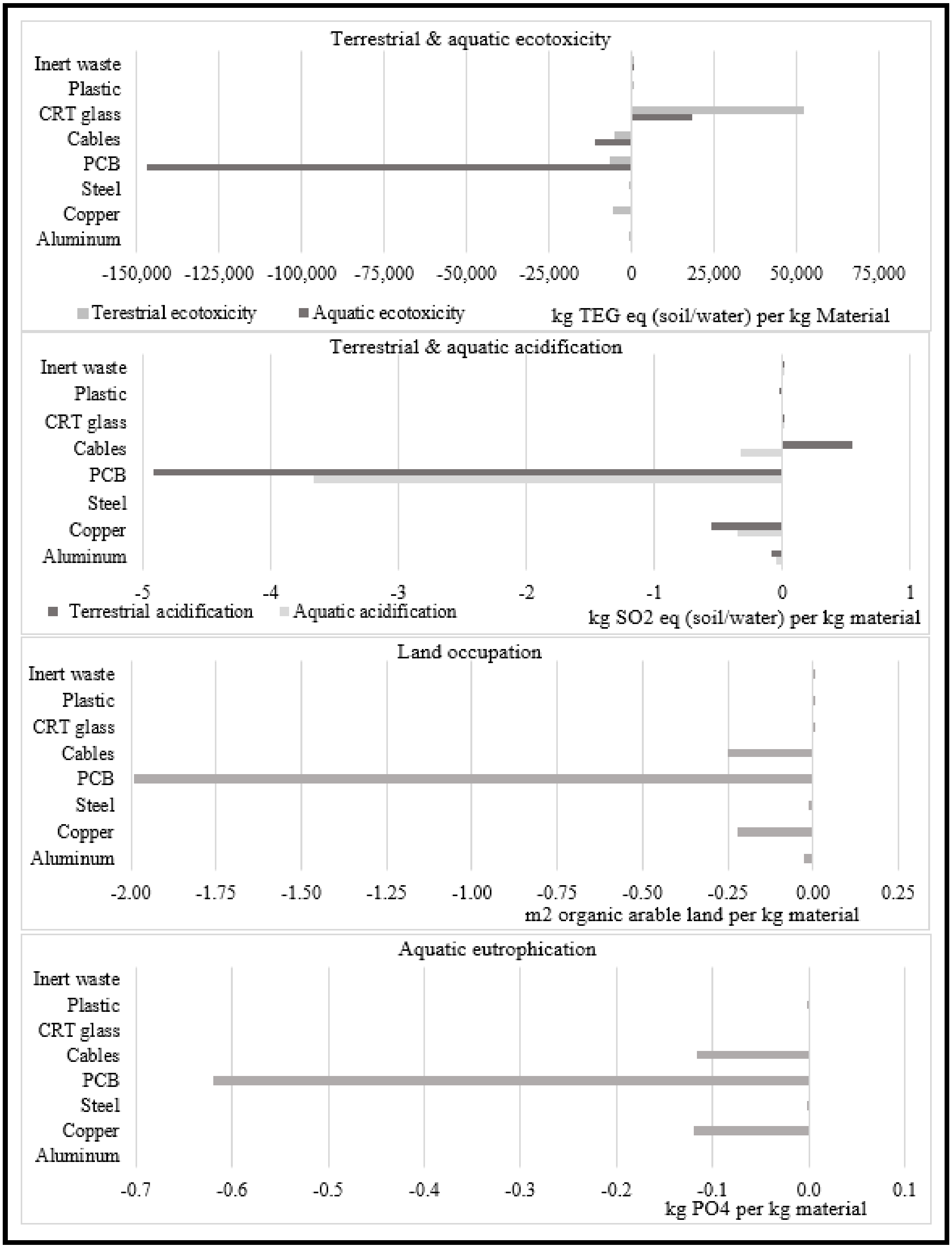


Figure 4-12 Ecosystem quality midpoint impact damage characterization per kg material.

Results of LCIA midpoint characterization for the climate change impact category are shown in Figure 4-13. PCBs have the largest avoided impact per kg recovered material (-18.8 kg CO_2 eq), followed by aluminum and cables (-7.0 and -2.8 kg CO_2 eq, respectively). The largest positive impact per kg is CRT glass at 0.005 kg CO_2 eq per kg material.

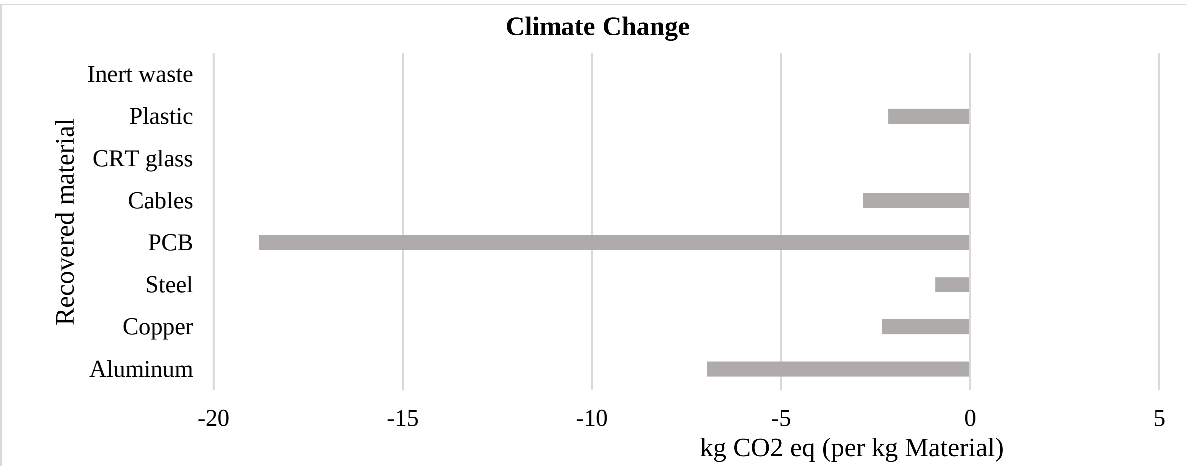


Figure 4-13 Climate change midpoint impact characterization per kg material.

The midpoint characterization categories for resources are shown in Figure 4-14. Copper and cables had the greatest avoided mineral extraction impact (-31.6 and -31.3 MJ surplus, respectively), while plastic had a damage of 0.003 MJ surplus/kg recovered. PCBs had the largest avoided non-renewable energy impact at nearly -295.0 MJ primary, while landfilling of inert materials and CRT glass had the largest positive impact at 0.2 MJ primary each.

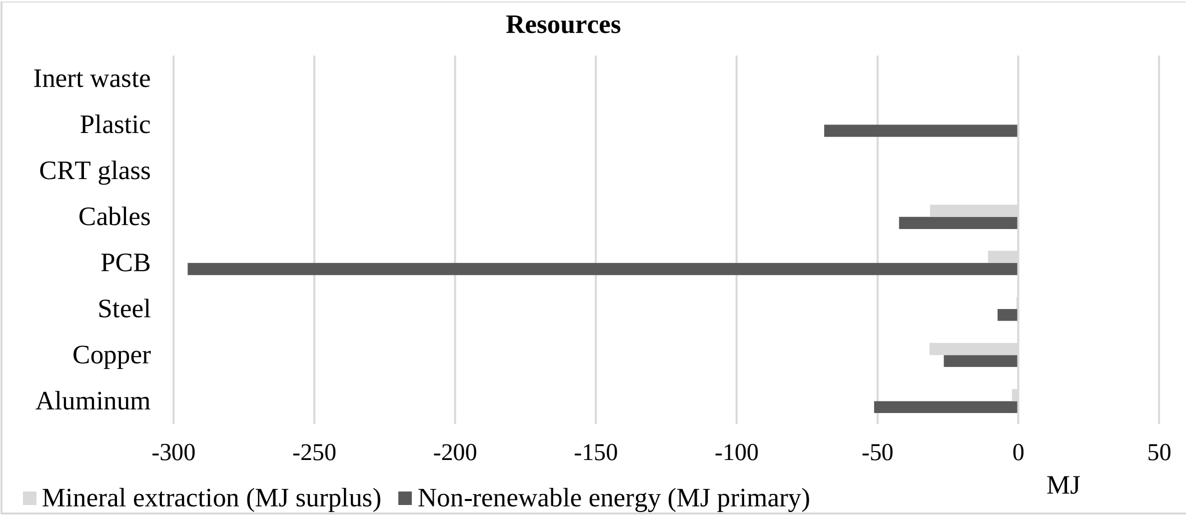


Figure 4-14 Resources midpoint impact characterization per kg material.

4.3.4 Per material LCIA endpoint results

The next four graphs show the results of the LCIA at endpoint level by material type, broken into its different processes. Figure 4-15 shows the endpoint human health damage per kg of each material type, the diamond in the figures representing the overall net impact for a given material type. There is a net benefit (negative damage) for all material types except three: inert waste, CRT glass, and cables that are burned. For the cables, the net impact is substantial with nearly 0.0001 DALY per kg of cable, which is nearly 30 times the next largest damage found in CRT screens. Burning (of cables), treatment, and transport make up the majority of the damages, while avoided materials account for the benefits. By treatment, we are referring to the processes of refining secondary scrap to the point where it is comparable with virgin materials for manufacturing.

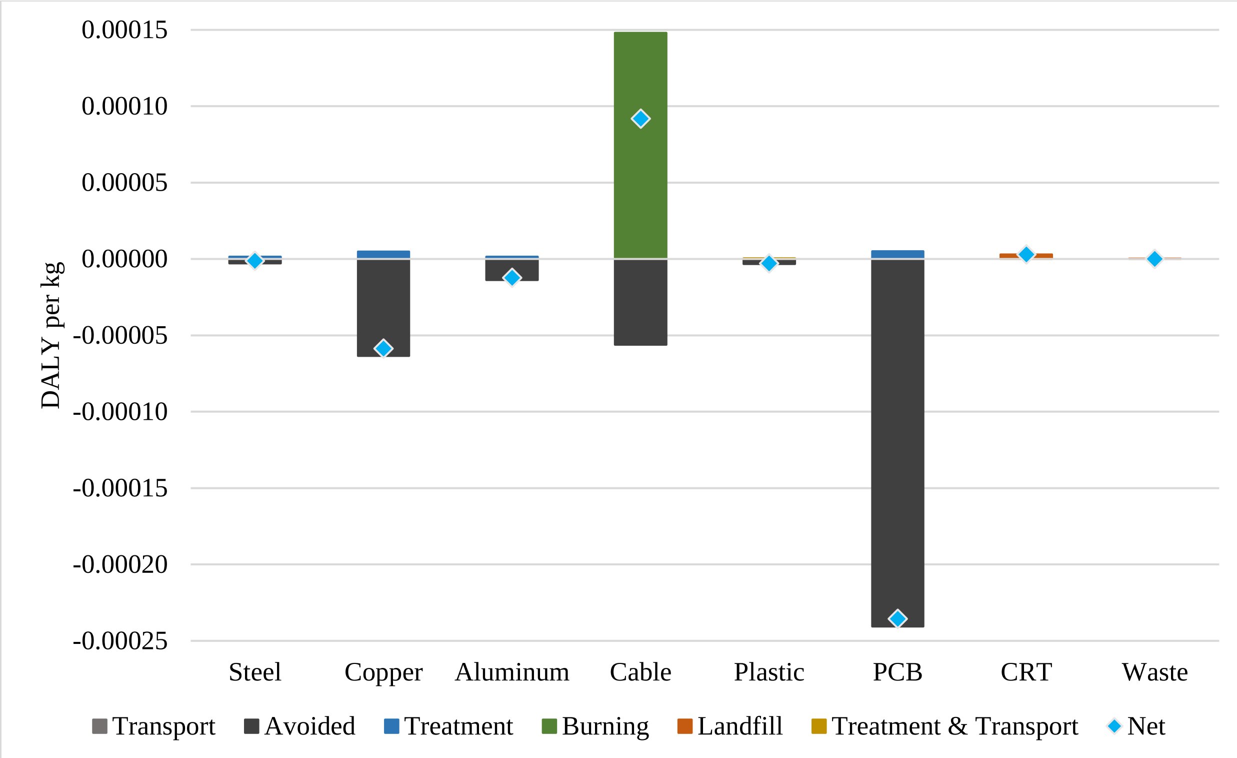


Figure 4-15 Endpoint damages on human health in DALYs per kg material or part. "Cables" in this figure and in subsequent figures include the burning and the copper recovery from these cables.

The results of the ecosystem quality damages by material type are shown in Figure 4-16. Once again, the processes of transport and treatment, and burning of cables all contribute to damages on the ecosystem quality. Plastic has a net damage of 0.07 PDF*m^2*yr per kg, while inert waste has a factor of 30 times smaller damage per kg. The improper landfilling of CRT glass generated a damage on ecosystem quality of 413 PDF*m^2*year per kg. PCB, followed by copper and cables, had the largest net benefit of all materials shown for ecosystem quality. Inert waste materials had a net positive (damaging) impact on ecosystem quality; however, the amount is negligible.

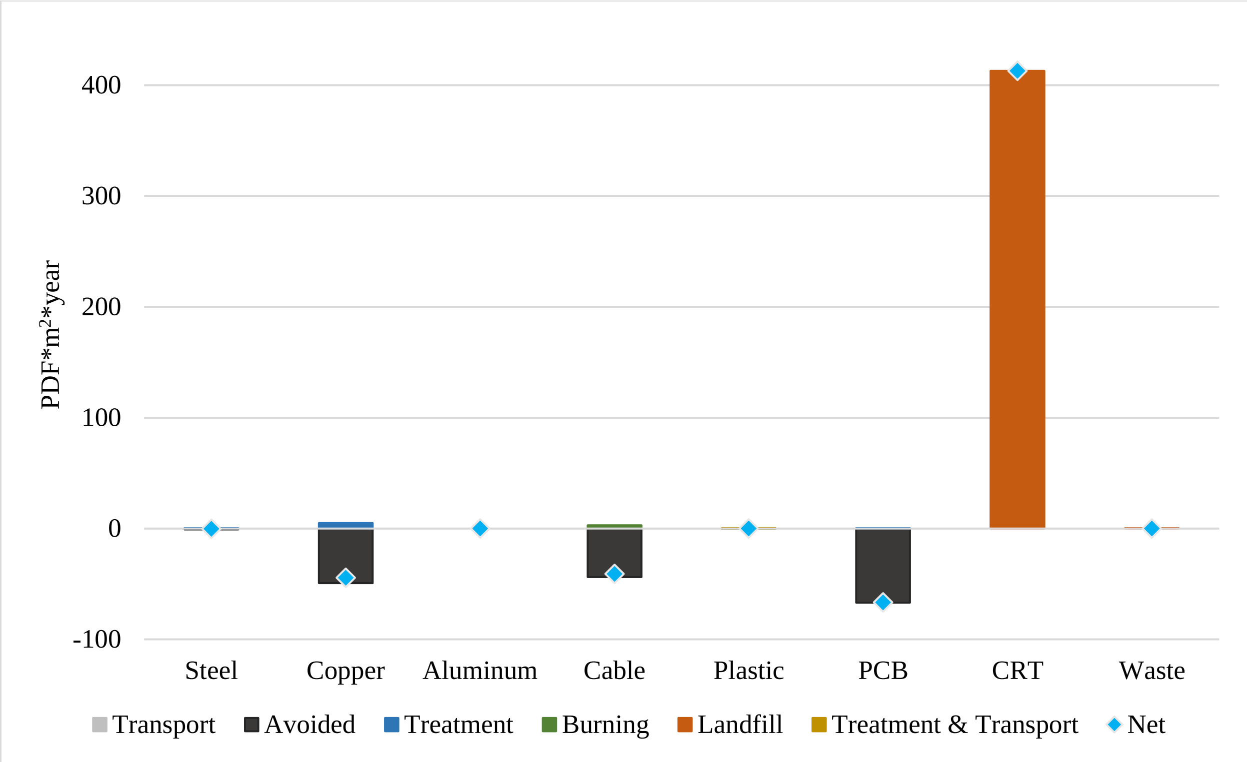


*Figure 4-16 Endpoint damages on ecosystem quality damages in PDF*m^2*year per kg material or part.*

The damages on climate change are shown below in Figure 4-17. Just as in the ecosystem quality damages category, PCBs result in the largest net avoided damages or benefits. Recycling of PCBs showed an avoided emission of 20 kg of CO_2 equivalents per kg recycled. The only net damages on climate change were found in CRT glass and inert waste, with a close to zero net damage of 0.005 kg of CO_2 eq per kg. Transport and treatment processes again accounted for the majority of the damages. Burning of copper wires accounted for some of the positive damages, however the benefit of avoided copper extraction was greater than the damages caused by burning.

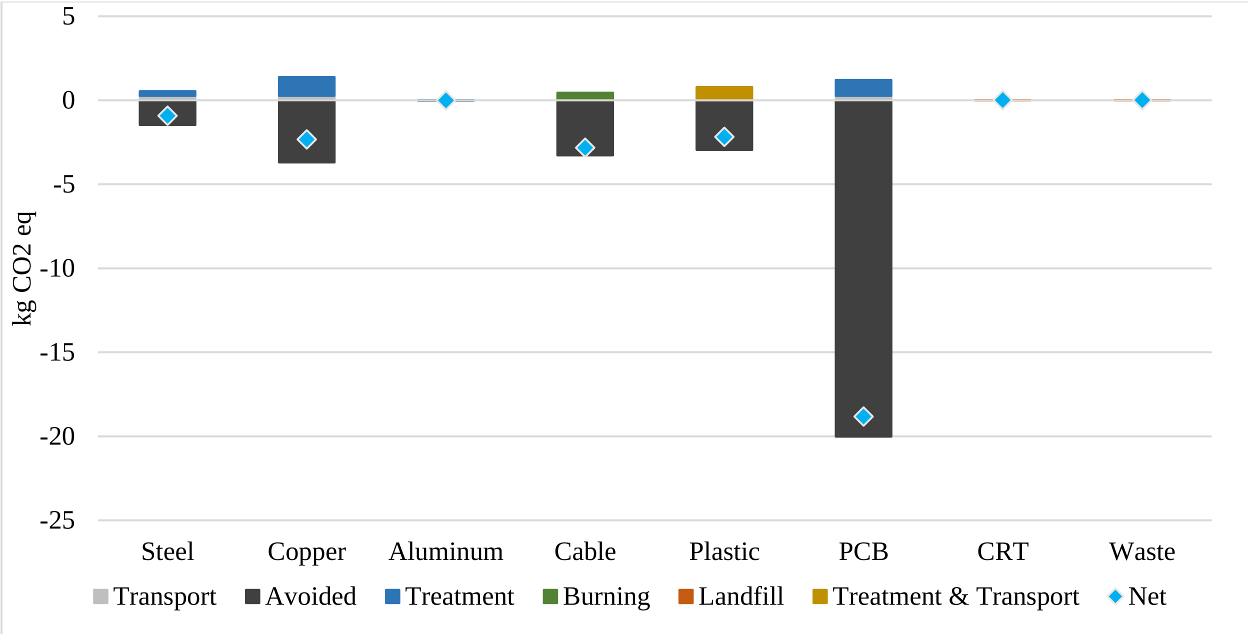


Figure 4-17 Endpoint damages on climate change in kg CO_2 eq per kg material or part.

Figure 4-17 presents the damages on resources, PCBs also having the largest net avoided damages to resources, driven by the avoided resource burden of primary gold, silver, and palladium (see appendix F). Recycling of PCBs results in a benefit of 306 MJ per kg PCB. Treatment and transport again accounted for the majority of the damages in resources. CRT glass and inert waste generated a close to zero net damage of 0.2 MJ per kg recycled.

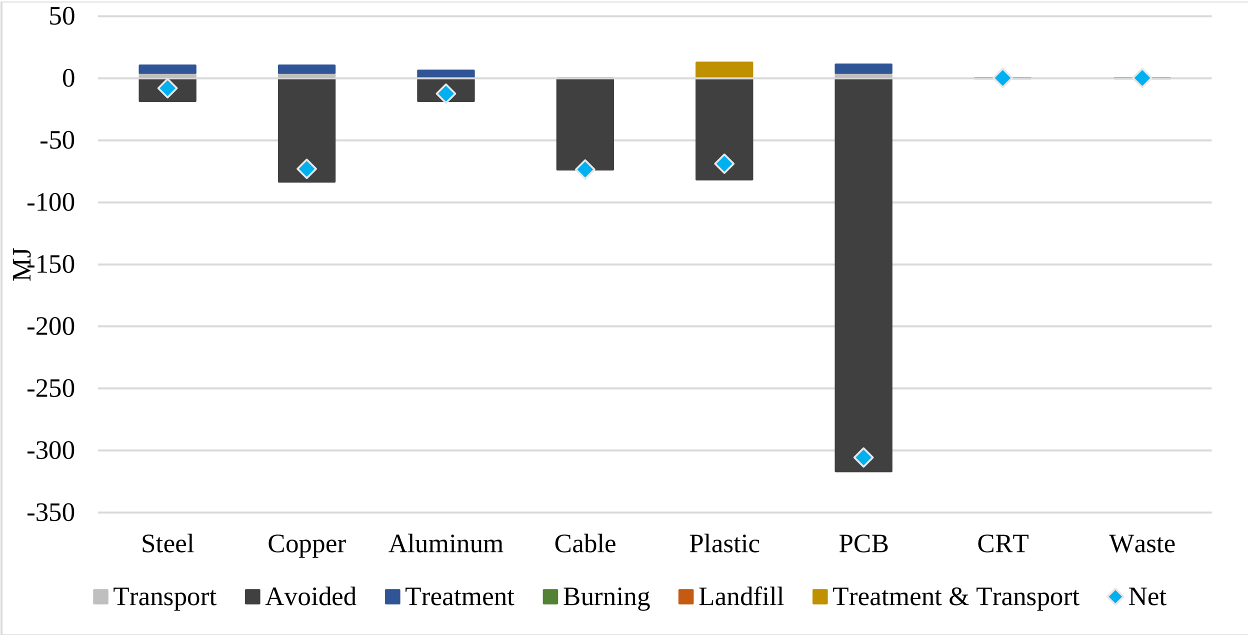


Figure 4-18 Endpoint damages on resources MJ per kg material or part.

The normalized impact by treatment stage for PCBs is further detailed in Figure 4-19. The avoided impacts of virgin gold, silver, and palladium extraction accounted for most of the avoided impacts. Similar trends were seen for aluminum, steel, copper, cable burning and recycling processes (Appendix F, Section F.2). ReCiPe results showed similar trends, where the avoided impacts of material recovery for metals resulted in an overall net avoided impact for that material when considering all processes, including transportation and refining (Appendix F, Section F.1).

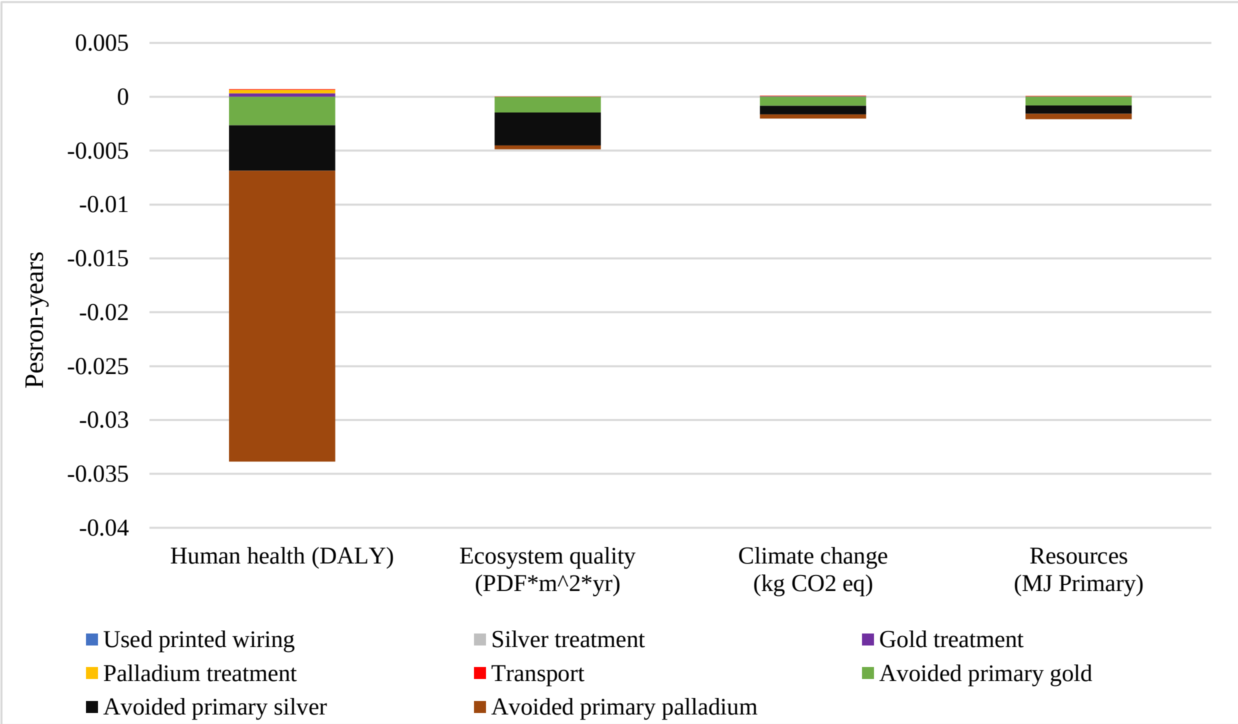


Figure 4-19 Normalized endpoint damages per kg printed circuit boards by material type and associated treatment.

Figure 4-20 shows the normalized impacts for burning of copper cables and copper recovery. The burning process results in impacts for all three damage categories relevant for this process: human health (0.021 person-years), ecosystem quality (2.06 E-4 person-years), and climate change (4.54E-5 person-years). However, we observe a net benefit for ecosystem quality and climate change when avoided mining of virgin copper is considered. Human health remains a net damage as the harms from burning of cables is larger than the benefit of avoided primary copper extraction. The ReCiPe method net avoided impact values were found for the cable burning process as well (Appendix F, Section F.2).

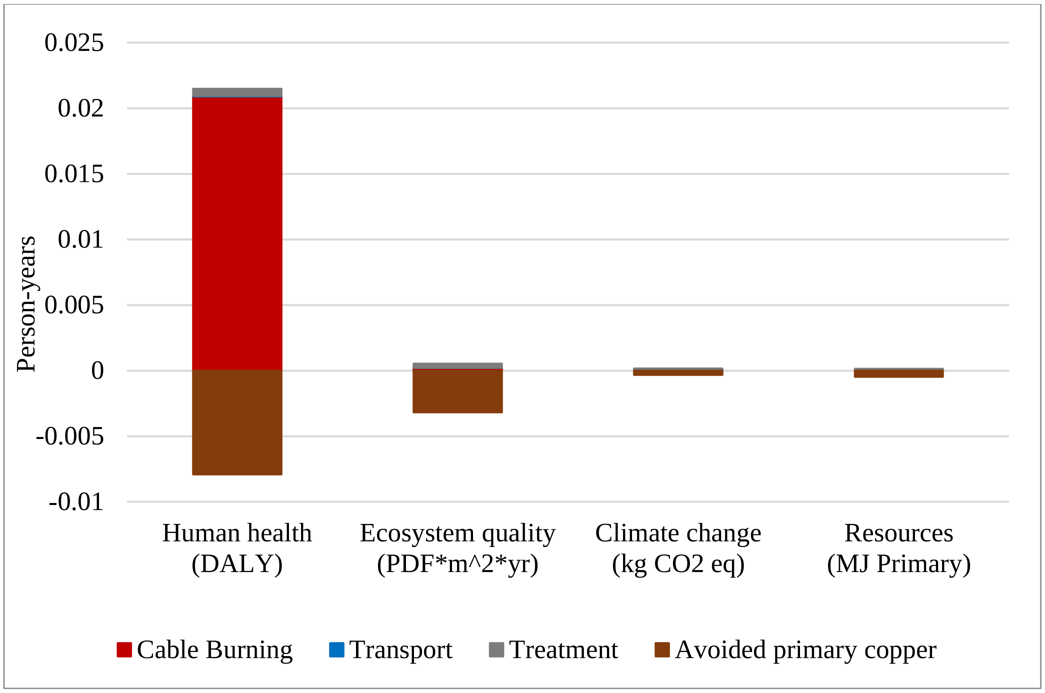


Figure 4-20 Normalized endpoint damage per kg recovered copper from burning, including associated treatments.

4.3.5 Per product LCIA results

Figure 4-21 shows the per-product LCIA endpoint damages on human health. All four products show a net benefit for human health, indicating that the avoided DALYs are larger than the accrued DALYs for the informal recycling process. Recycling of washing machines and refrigerators both resulted in a net avoided impact of nearly -0.0001 DALYs per product The PCBs recovered from televisions had the overall largest avoided impact on human health, resulting in a net benefit of -0.0002 DALYs per product. Impact 2002+ estimated that the process of landfilling leaded CRT glass from televisions results in a net damage of 4.16E-5 DALYs. Fans recycled by informal methods resulted in the smallest net avoided human health impact, about 1/10th as great as washing machines or refrigerators. Tools and electricity to power the electric drill were negligible compared to the total human health impact per product (For more information, see Appendix F, Section F-1).

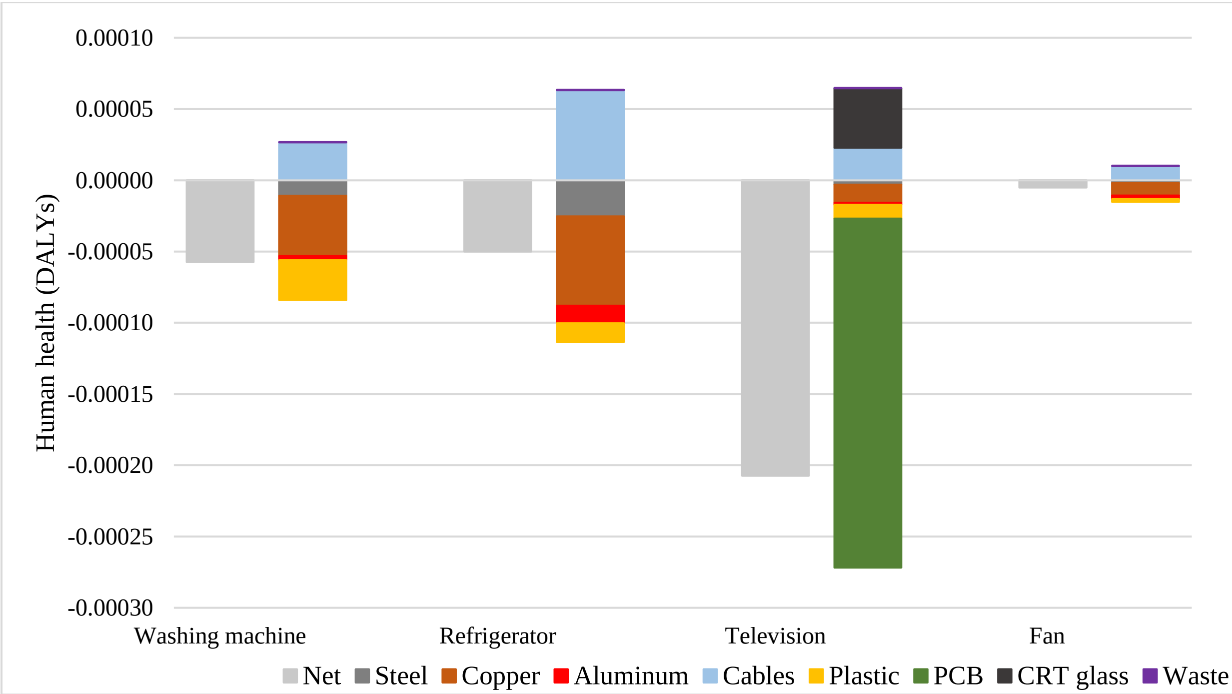


Figure 4-21 Human health impacts in DALYs of recovered materials per product piece. "Cables" in this figure and in subsequent figures include the burning and the copper recovery from these cables.

Figure 4-22 shows the endpoint damages on ecosystem quality of recycling each of the four products by informal methods is shown in. The net ecosystem quality impact shown for each product is negative with the exception of the television due to the CRT glass. Washing machines result in a net benefit for ecosystem of -46 PDF*m^2*yr, meaning there is a net avoided potential loss equivalent to 100% of species lost over 46 m^2 of Earth's surface during the course of one year. Recycling of one refrigerator resulted in a net avoided impact on ecosystem quality of 82 PDF*m^2*yr, while fans had a net avoided impact of 12 PDF*m^2*yr. Tool use for all four products was negligible in the LCIA calculations (See Appendix F, Section F.1).

If CRT screens are removed from the LCIA, then televisions have a net avoided impact on ecosystem quality of 90.0 PDF*m^2*yr. However, if CRT screens are included, then the damage is substantial, with ecosystem quality damages of 5,510.0 PDF*m^2*yr. Landfilling of

CRT glass in the average television by this community results in large damages to the ecosystem. Though this impact would be offset if the landfilling impact of the base scenario was considered in a comparative assessment, this emphasizes the importance of a proper disposal of lead in these CRT screens.

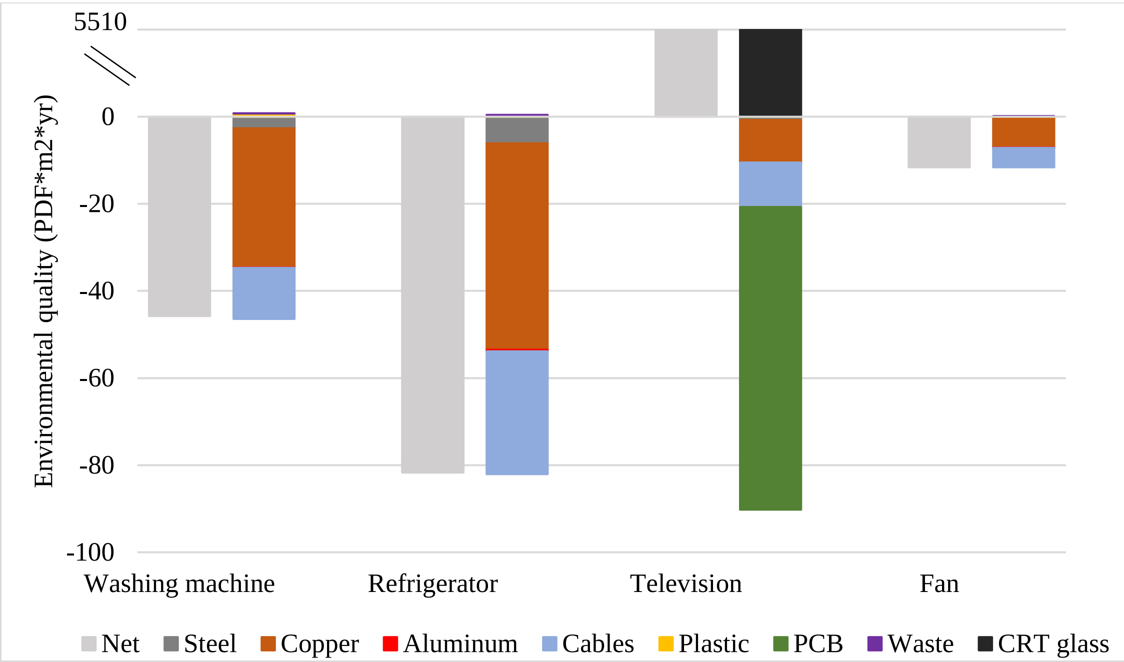


*Figure 4-22 Ecosystem quality damage in PDF*m^2*yr per product piece, differentiated by recovered materials (excludes leaded CRT glass).*

Figure 4-23 shows the climate change impacts for the four selected e-waste products. All four products have a net benefit for climate change. The net avoided climate change damages are largest for refrigerators (-25.4 kg CO_2 eq per product) and smallest for fans (-2.7 kg CO_2 eq per product). Landfilling of inert materials were responsible for the damage associated with each product, and CRT glass had an impact of 0.071 kg CO_2 eq per kg glass. The use of tools was negligible in terms of climate change damages (Appendix F, Section F.1).

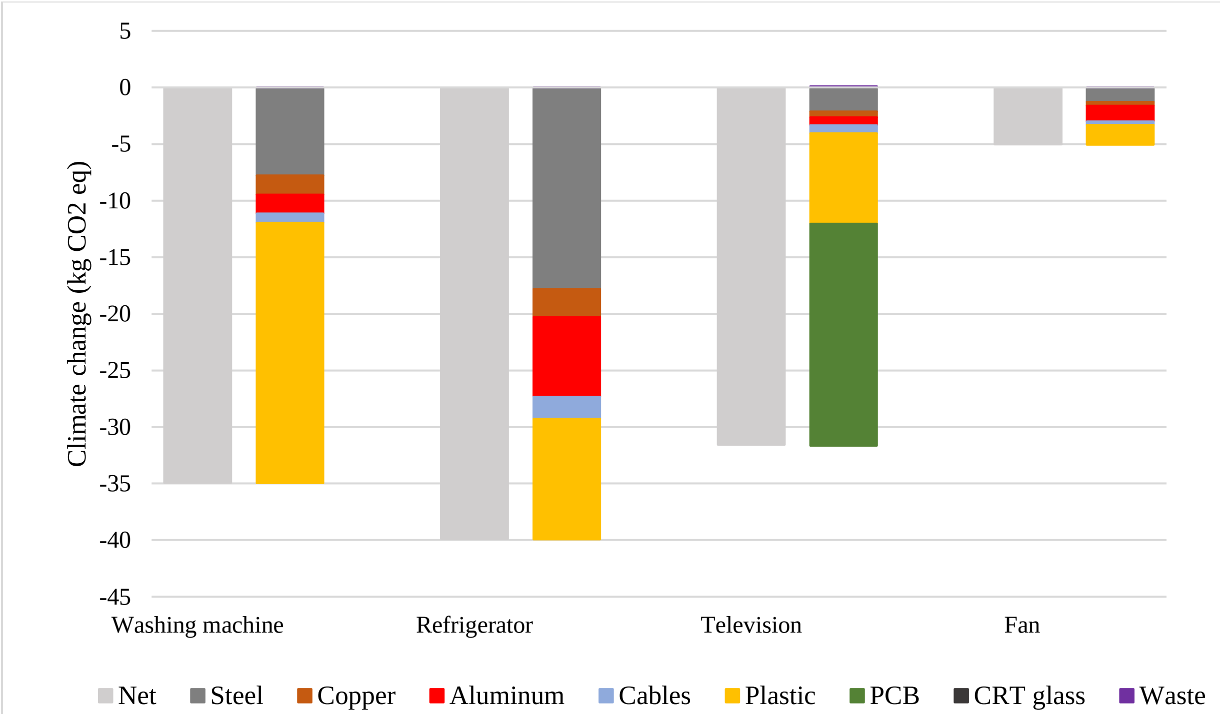


Figure 4-23 Climate change potential (kg CO_2 eq per product piece) for e-waste products, differentiated by recovered material.

Figure 4-24 displays the final endpoint damage on resources. For all four e-waste products, there is a net benefit on resources per piece of recycled product. The largest net avoided resource per product is found for washing machines (-875 MJ), followed by refrigerators (-660), televisions (-625 MJ) and fans (-93 MJ). Once again, inert landfill waste is responsible for the resource damage across all four products, as well as CRT screens for TVs. The impact of tool use on resources was negligible (see Appendix F, Section F.1).

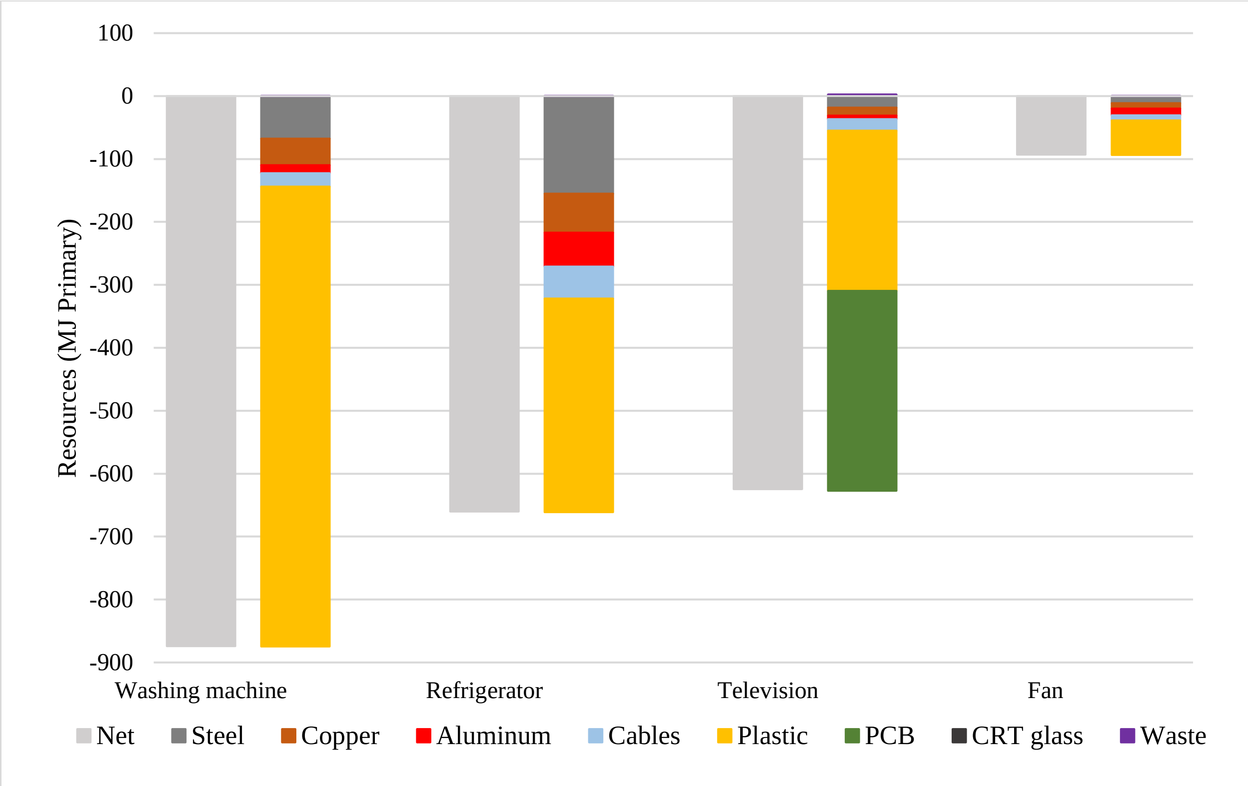
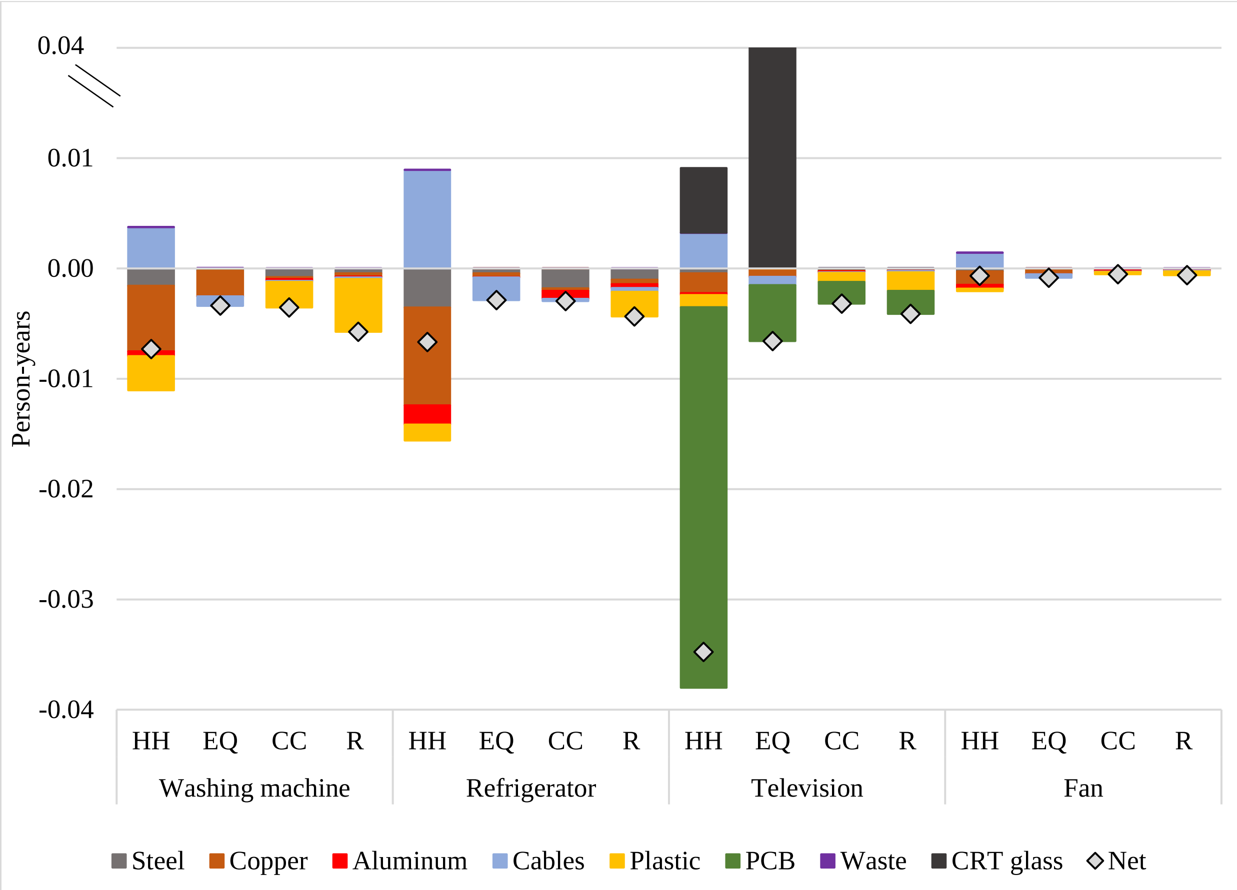


Figure 4-24 Impact on resources (MJ Primary per product piece) for e-waste products, differentiated by recovered material.

Figure 4-25 Figure 4-25 Normalized endpoint damage scores per piece of each electronic product, differentiated by material type, and excluding CRT glass.provides the normalized scores for each damage endpoint category. The CRT television screen is included to show the substantial importance of this material on overall impact, with a normalized impact score of 0.006 person-year/TV for human health, 0.41 person-year/TV for ecosystem quality, 0.00001 kg person-year/TV for climate change, and 0.00001 person-year/TV for resources. Cables have the largest impact on human health, with the recovery and burning of cables from one refrigerator having a normalized damage of 0.009 person-year. This can be interpreted to mean that informal recycling of cables from one refrigerator has an equivalent impact on human health to the pollution generated by 0.009 persons during one year.



HH= human health; EQ = ecosystem quality; CC = climate change; R = resources.

Figure 4-25 Normalized endpoint damage scores per piece of each electronic product, differentiated by material type, and excluding CRT glass.

4.3.4 Environmental impacts and benefits at community level

The results of the MFA conducted in Village 4 for the selected four e-waste products are combined with the per-product LCA results to determine monthly environmental benefits and impacts associated with the Village 4 recovering activities (Table 4-6). Each month, the community avoids 0.2 DALYs in health damages (or 2.4 DALY per year activity), 58,300 kg CO_2 eq in climate change damages, and 873,000 MJ in resource damages through the recycling of washing machines, refrigerators, televisions, and fans. The community also creates ecosystem quality damages in the amount of nearly 3 million PDF*m^2*yr per month.

Table 4-6 Endpoint damages associated with all four e-waste products recovered in one neighborhood per month.

Endpoint damage	Washing machine	Refrigerator	Television	Fan	Sum
Human health (DALY)	-0.03	-0.02	-0.12	-0.01	-0.2
Ecosystem quality (PDF*m^2*yr)	-20,583.1	-39,232.1	3,058,069.7	-13,737.8	2,984,516.7
Climate change (kg CO_2 eq)	-15,719.8	-19,150.3	-17,513.3	-5,955.8	-58,339.2
Resources (MJ primary)	-393,458.2	-316,817.9	-51,743.9	-110,480.3	-872,800.3

4.4 Discussion

To our knowledge, this is the first study to conduct a combined MFA and LCA using primary data from small-scale informal e-waste recycling operations. Through the examination of four e-waste products, human health, environmental, climate change, and resource impacts were characterized.

4.4.1 Material flow and economics

Our results showed that one village in the studied community had 14 households that engaged in e-waste recycling activities. Each month, informal recyclers in this village process nearly 40,000 kg of e-waste for four product types, of which approximately 29,000 kg is recyclable materials. Informal recyclers were able to recover an average of 93% of materials across the four products. This high recovery rate is likely driven by the economic opportunity derived from recovery of materials, particularly copper [68]. The unrecovered 7% was typically lost to the soil at the work site. E-waste recyclers may have taken opportunities to occasionally collect lost materials; however, work sites were littered with e-waste materials suggesting that at least some of the material is never recovered.

The masses of recovered materials agree with the limited information available on similar electronic products in the literature. For example, in CRT TVs we found a mean copper recovery weight of 0.42 kg, or 1.04% (not including copper content in PCBs). A 2007 study found copper concentrations of 3.4% total weight in CRT TVs, while a 2015 study found 0.66 kg of copper in a CRT TV [31], [91]. Some of the differences found in weight and percent composition are due to variations in product design in different regions of the world, while some of the difference is due to the material recovery potential associated with the considered recycling methods (manual versus machine) and the ability to recycle individual materials from PCBs. Our results agree with a study conducted on the formal sector in the United States which found that of the materials recovered, metal provided the greatest economic reward [92]. A 2015 study found that one CRT television generates 18 Euros/product [31], while our results showed a total value of approximately 4 Euros, and a value added of just 1.5 Euros. This difference is most likely due to the ability of the formal sector to recover all components of the CRT screen, including lead, glass, and electron gun materials, as well as the ability to recycle and refine PCB boards rather than selling the boards to someone else for recovery. In addition, the size of the television makes a difference on the overall value, and it is possible that televisions being recycled in Thailand are smaller than those being recycled in Europe.

The selling price of raw materials was comparable in the study site to that reported in the literature [52], [65]. The net value added from these four products in Village 4 was more than 157,000 THB, which would be enough to pay for 24 full-time minimum wage workers among 14 households. Many more people in the community are likely to benefit from e-waste activities beyond just recyclers. Scrap buyers, sellers of e-waste products, welders, persons engaged in electronic repair, and other sectors would benefit from e-waste economic activities. Given the need to subsidize formal recycling to generate a profit [48], the informal sector may contain lessons for profitability of e-waste recycling.

4.4.2 LCA results per material or e-waste part

Recovery and recycling of metals from e-waste resulted in a net avoided damages, for most midpoint and endpoint categories. This indicates that there is overall a net benefit in terms of human health, ecosystem quality, global warming, and resources. These beneficial trends might be reduced in the future, as electronic products increasingly use a mixture of metals and materials, making it more difficult to recover, recycle and reuse these mixtures [68].

Plastic recycling showed a benefit for all damage categories except ecosystem quality, which had a net damage impact of 0.07 PDF*m^2*yr per kg recovered (See Appendix F). A study examining the benefits of plastics recycling in the formal sector compared to virgin plastics similarly found a 25% increase in terrestrial ecotoxicity in the later processes compared to the former [93]. However, compared to alternative scenarios of production of virgin plastics in European countries, the literature estimates that recycling of e-waste plastics results in fewer damages than production of virgin materials [79], [93]. The ReCiPe results showed an overall net benefit for plastics recycling (Appendix G).

Burning of copper cables, including the subsequent recovery and recycling of copper from the cables, resulted in a damage of 9.2E-05 DALYs using the Impact 2002+ method, versus an avoided -2.3E-04 DALYs using the ReCiPe method. Although both methods show an overall human health damage from the burning of copper cables, the avoided emissions calculated by ReCiPe are slightly higher than for Impact 2002+ therefore yielding a net benefit. Net ecosystem and resources impact were estimated as beneficial by both methods. Electronic cable coating is made of poly vinyl chloride (PVC) plastic, which releases harmful toxins when combusted, including PVC, brominated flame retardants, polycyclic aromatic hydrocarbons, and dioxins [96], [97]. These can be particularly harmful to workers who engage directly in burning activities, as they often stay near the burning cables throughout the process in the Thai research community but was not directly considered in the present approach that focused on ambient air emissions and associated exposure of the general population.

This study suggested an average of 0.9 kg Pb per CRT screen, based on Mear, et al., 2010 combined with field data [84]. This estimate is slightly below the estimate of 1.2 kg Pb/CRT screen reported by Meng et al., [94]. Combined with the product flow MFA results from Village 4, we can then estimate that over 6,000 kg of Pb are being improperly disposed of in the local dump site each year from this one village alone. A study examining leachability of PbO from CRT glass found that 1% of Pb was released from CRT glass after a 10-step leaching test and concluded that Pb would continue to leach for a long period of time [95]. Conditions such as increased water saturation and size of broken glass are known to increase lead leaching in the environment [96], [97]. Although it is not possible to exactly model the timescale at which the Pb will leach from the CRTs disposed of in the study dump site, the results indicate that the environmental and human health damages caused by the leaching of lead are substantial and constitute a health concern for the community. The dump site is not lined, and so lead can leach into surrounding soil and water, contaminating water, crops, humans, and the ecosystem. The LCA results using Impact 2002+ methods indicate that handling of 1 kg of CRT screen results in human health damages of 3.07E-06 DALYs, relatively close to the ReCiPe method of 1.64 E-06 DALYs, considering that damage on human health are to be interpreted on a log scale due to their high uncertainties.

Recycling of PCBs resulted in net avoided damages for all endpoint categories. Manufacturing of PCBs is energy-intensive, as is the extraction of the precious minerals. A 2012 study found that the greatest environmental impacts in the manufacturing of a CRT television set was due to PCB production [71]. Our results show that for the end-of-life informal e-waste treatment scenario, PCBs provide the greatest avoided damages the benefit. Results from Impact 2002+ and ReCiPe methods showed similar trends. Although endpoint categories differed, PCBs in both models were shown to drive the net avoided human health, ecosystem and resource benefits in CRT television recycling.

4.4.3 LCA results per product

All four products resulted in a net benefit for all endpoint damage categories except for televisions in environmental impacts (large damages from CRT screen landfilling). Our results demonstrate that informal e-waste recycling provides environmental human health, climate change, and resource benefits through avoided impacts of virgin metals substituted by the secondary recycled metals. This net benefit will be further increased when considering the alternative scenario (avoided landfilling of e-waste). This suggests that products with similar components and low concentrations of hazardous chemicals, such as washing machines and fans, might be advantageous to recycle manually in the informal sector, while products with hazardous materials, like CRT televisions, are damaging if not properly disposed of. Dismantling of e-waste by informal e-waste workers with downstream processes, including recovery of dangerous, precious, and trace materials, being completed by more formalized operations may be advantageous for both sectors [44], [67]. Manual labor, high percent recovery of materials, and efficiency in manual collection and sorting of e-waste are all beneficial aspects of the informal sector resulting in avoided damages.

Despite some differences in the LCIA results for recovered material types, the overall benefits at the product level are similar and would provide decision-makers with similar information. For example, with either method, we see that although televisions have the largest net avoided impact, they also present a large threat to human health due to the lead content of the CRT glass. It is essential to ensure a proper disposal and treatment of both CRT glass lead content and of copper wires. However, the severity and resulting net impacts on two vital processes, improper landfilling of CRT televisions and burning of copper cables, differs between the two. First, landfilling of the CRT could occurs both in the recovery scenario and in the reference landfilling scenario and will therefore be offset in a comparative assessment between these scenarios. In contrast the burning of wires might not occur in the landfill and this impact will therefore remain even when comparing to landfill. In addition, results from ReCiPe the hazards associated with burning of copper wires are compensated by the avoided impacts from the substituted virgin material, yielding a net avoided for all damage categories, whereas Impact 2002+ was giving a net damage for human health. In this case, the net damage is the difference between two larger numbers and can therefore change sign depending on the magnitude of the burning impacts assessed by each method.

Studies have shown that during pre-processing steps, such as those performed in our study community, the informal sector actually produces higher yields than mechanized processes found in the formal sector [44]. In addition, the manual process of sorting and disassembly in the informal sector utilizes less energy and causes fewer environmental impacts than the highly mechanized formal sector [98]. However, the recovery of individual metals may be more important in terms of environmental impacts than energy expenditure during formal recycling [99].

4.4.4 Comparison with landfilling scenario

The life cycle assessment in this chapter considered the impacts associated with informal e-waste recycling. If we were to compare these impacts with a landfill scenario, we would subtract emissions associated with the landfilling of e-waste materials. First, we subtracted impacts of the landfill scenario with the informal recycling scenario, then the net difference in damages for the CRT TV would be 0 since the materials would generate the same landfill related impacts in both cases. A proper disposal of lead in these CRT screens would then even further improve the comparative advantage of the material recovery. We would expect to see a further increase in net avoided emissions, in particular for heavy metals in the PCB. A simplified LCA study from 2006 found that, compared with formal recycling, landfilling of e-waste had larger damages than recycling as long as the distance travelled did not cause even greater damages in the form respiratory inorganics and fossil fuel use [76]. However, this study did not look at the avoided emissions in the recycling scenario, and if included, may have changed the landfilling scenario to be more damaging regardless of distance. This 2006 study did not consider the impact of different materials within the landfill. There is arguably an even greater benefit in dismantling and recycling of e-waste materials if we consider the avoided impacts of some materials, like PCB in landfills. PCBs are known to leach lead and other hazardous materials [97], which might lead to substantial ecosystem quality damages from landfilled e-waste containing PCB. In contrast no offset can be expected for the cables, since the wire burning only occurs in the e-waste recovery scenario, emphasizing the importance of proper copper extraction from wires.

4.4.5 Public health implications

This study has demonstrated that while informal e-waste dismantling can offer benefits depending on the product, improper handling of some products has the potential to cause damages. Despite its label as a hazardous waste in the U.S. and globally, and a UN ban on cross-border transportation, improper disposal of e-waste continues to plague the globe. In 2010 in the U.S. alone, an estimated seven to nine million computers were landfilled [25]. While many authors have suggested a need for formalization of the sector, the informal e-waste sector continues to grow [30], [100]. This growth, combined with the results from this study, suggest a need to shift focus to providing recommendations for informal e-waste recyclers, to focus on dismantling, while the final extraction and recycling step are better performed by formal and regulatory compliant actors and processes.

Demand for CRT TVs and computer screens has dramatically fallen due to development and growth of flat-screen technologies [101]. Although no estimate exists for the current number of CRT screens that will one day need to be recycled, it is reasonable to expect that the time frame during which CRT recycling will be prevalent activity is limited. This, however, does not limit the significance of our study. Lead is contained in a variety of electronic items, and so the impacts from lead in CRTs can be applied to other e-waste products as well. Secondly, lead is a persistent compound that remains in the environment for long periods of time indicating that the impacts of lead from improperly recycled e-waste will far out-live the time period when CRTs are recycled. Finally, the findings of our study provide insight into how future e-waste streams may impact human health, ecosystem quality, climate change, and resources for other hazardous materials that may be contained in e-waste. Although the exact damage quantities among the different categories will vary depending on product type, we have provided a model for how to consider the different processes.

4.4.6 Limitations

This study had several important limitations. First, we did not consider what happens to waste materials. During visits to the study site, for examples, it was observed that the toxic foam liner of refrigerators often served dangerous purposes, including outdoor storage bins for other types of e-waste, fuel to light fires, and was consumed by free-range chickens. Similarly, we did not consider that unrecovered material may contain metals or other hazardous substances that enter the environment and may result in ecosystem and human health damages.

Next, this study only considered four product types. Other e-waste products that contain different materials may produce very different damages. Additionally, products of the same type but manufactured differently may also have different impacts. We were unable to include all chemicals and processes in the analysis. Older refrigerators contain harmful CFCs and other chemicals that are released early in the recycling process [35]. Similarly, electron guns contain nickel [102]. If not handled properly, these chemicals can cause environmental damage.

4.4.7 Future directions

This study uses primary field data to conduct for the first time a combined MFA and LCA analysis of informal e-waste dismantling and recycling. In order to promote a healthy, environmentally-conscious informal e-waste sector, additional combined MFA and LCA studies are needed. Understanding which manual recycling techniques result in the highest recovery yield will improve environmental impacts as well as worker income. Small-scale MFAs are needed to track the amount of e-waste being processed in the informal sector to allow for estimations of impacts. LCA studies that examine which products and processes have larger associated damages will help form recommendations for the industry to make decisions about which products should only be handled by formal recycling methods. Finally, comparison studies are needed in other study sites as recycling methods depend on culture, product availability, economics, and regulations. For example, e-waste recyclers in Chile were observed to only recover materials which they were able to sell (i.e. plastic was considered as a waste whereas it is sold in Thailand), which would likely result in lower recovery yields (field observations by author). Further studies would help to contextualize our results.

4.5 Conclusions

This study has shown that informal e-waste recycling can provide net human health, ecosystem quality, climate change, and resources benefits in the form of avoided emissions for some products. In addition, informal e-waste recycling offers important economic benefits for our study population and other communities around the globe. Policy-makers and scientists should focus on recommendations designed to focus the informal sector on dismantling tasks and ensure that the recycling of products that contain hazardous chemicals, like CRT glass screens or copper wires are properly handled in environmentally optimized processes.

4.6 Bibliography

1. Baldé, C. P., Forti, V., Kuehr, R. & Stegmann, P. The global e-waste monitor - 2017. (2017).
2. Peralta, G. L. & Fontanos, P. M. E-waste issues and measures in the Philippines. J. Mater. Cycles Waste Manag. 8, 34–39 (2006).
3. Ladou, J. & Lovegrove, S. Export of electronics equipment waste. Int. J. Occup. Environ. Health 14, 1–10 (2008).

4. Sthiannopkao, S. & Wong, M. H. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Sci. Total Environ. 463–464, 1147–1153 (2013).

5. Wang, Z., Zhang, B. & Guan, D. Take responsibility for electronic-waste disposal. Nature 536, 23–25 (2016).

6. Schmidt, C. W. e-Junk explosion. Environmental Heal. Perspect. 110, A118-194 (2002).

7. Matthews, H. S., McMichael, F., Hendrickson, C. & Hart, D. Disposition and end-of-life options for personal computers. Green Des. Initiat. Tech. Rep. (1997). doi:10.1111/j.1475-4762.2008.00860.x

8. Environmental Protection Agency, U. et al. Assessing trends in material generation, recycling, composting, combustion with energy recovery and landfilling in the United States. (2014). doi:10.1111/j.1524-4725.2012.02551.x

9. Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M. & Böni, H. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25, 436–458 (2005).

10. Streicher-Porte, M. et al. Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi. Environ. Impact Assess. Rev. 25, 472–491 (2005).

11. Lu, B., Song, X., Yang, J. & Yang, D. Comparison on End-of-Life strategies of WEEE in China based on LCA. Front. Environ. Sci. Eng. 11, (2017).

12. Chi, X., Streicher-Porte, M., Wang, M. Y. L. & Reuter, M. A. Informal electronic waste recycling: A sector review with special focus on China. Waste Manag. 31, 731–742 (2011).

13. Tanskanen, P. Management and recycling of electronic waste. Acta Mater. 61, 1001–1011 (2013).

14. Tansel, B. From electronic consumer products to e-wastes : global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35–45 (2009).

15. Treblin, J. Informal recycling of e-waste a serious problem, expert says. Our World: Brought to you by United Nations University (2013). Available at: https://ourworld.unu.edu/en/informal-recycling-of-e-waste-a-serious-problem-expert-says. (Accessed: 12th January 2019)

16. Fu, J. et al. Influence of e-waste dismantling and its regulations: temporal trend, spatial distribution of heavy metals in rice grains, and its potential health risk. Environ. Sci. Technol. 47, 7434–7445 (2013).

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

18. Grant, K. et al. Health consequences of exposure to e-waste: a systematic review. Lancet. Glob. Heal. 1, e350-61 (2013).

19. Tao, L. et al. Aquatic bioaccumulation and trophic transfer of tetrabromobisphenol-A flame retardant introduced from a typical e-waste recycling site. Environ. Sci. Pollut. Res. 23, 14663–14670 (2016).

20. An, T. et al. Pollution profiles and health risk assessment of VOCs emitted during e-waste dismantling processes associated with different dismantling methods. Environ. Int. 73, 186–94 (2014).

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

22. Zhang, K., Schnoor, J. L. & Zeng, E. Y. E-waste recycling: where does it go from here? Environ. Sci. Technol. 46, 10861–10867 (2012).

23. Puckett, J. et al. Exporting Harm. 1–51 (2002). doi:10.1016/S0021-9150(97)84578-9

24. Singh, N., Li, J. & Zeng, X. Global responses for recycling waste CRTs in e-waste. Waste Manag. 57, 187–197 (2016).

25. Kahhat, R. et al. Exploring e-waste management systems in the United States. Resour. Conserv. Recycl. 52, 955–964 (2008).

26. Sthiannopkao, S. & Wong, M. H. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Sci. Total Environ. 463–464, 1147–1153 (2013).

27. Pinto, V. N. E-waste hazard: The impending challenge. Indian J. Occup. Environ. Med. 12, 65–70 (2008).

28. Terazono, A. et al. Current status and research on E-waste issues in Asia. J. Mater. Cycles Waste Manag. 8, 1–12 (2006).

29. Heeks, R., Subramanian, L. & Jones, C. Understanding e-Waste Management in Developing Countries: Strategies, Determinants, and Policy Implications in the Indian ICT Sector. Inf. Technol. Dev. 21, 653–667 (2015).

30. Rochat, D., Rodrigues, W. & Gantenbein, A. India: Including the Existing Informal Sector in a Clean E-Waste Channel. 19th Waste Manag. Conf. IWMSA 477–483 (2008).

31. Cucchiella, F., Adamo, I. D., Koh, S. C. L. & Rosa, P. Recycling of WEEEs : an economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev. 51, 263–272 (2015).

32. Julander, A. et al. Formal recycling of e-waste leads to increased exposure to toxic metals: an occupational exposure study from Sweden. Environ. Int. 73, 243–51 (2014).

33. Ceballos, D. M. & Dong, Z. The formal electronic recycling industry: Challenges and opportunities in occupational and environmental health research. Environ. Int. 95, 157–166 (2016).

34. Ceballos, D., Beaucham, C. & Page, E. Metal Exposures at three U.S. electronic scrap recycling facilities. J. Occup. Environ. Hyg. 9624, 00–00 (2016).

35. Robinson, B. H. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–91 (2009).

36. Chancerel, P., Meskers, C. E. M., Hagel??ken, C. & Rotter, V. S. Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. J. Ind. Ecol. 13, 791–810 (2009).

37. Shuva, M. A. H., Rhamdhani, M. A., Brooks, G. A., Masood, S. & Reuter, M. A. Thermodynamics data of valuable elements relevant to e-waste processing through primary and secondary copper production: A review. J. Clean. Prod. 131, 795–809 (2016).

38. Li, J., Zeng, X., Chen, M., Ogunseitan, O. A. & Stevels, A. 'Control-Alt-Delete': rebooting solutions for the e-waste problem. Environ. Sci. Technol. 49, 7095–7108 (2015).

39. Kaya, M. Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manag. 57, 64–90 (2016).

40. Herat, S. & Agamuthu, P. E-waste: a problem or an opportunity? Review of issues, challenges and solutions in Asian countries. Waste Manag. Res. 30, 1113–1129 (2012).

41. Pariatamby, A. & Victor, D. Policy trends of e-waste management in Asia. J. Mater. Cycles Waste Manag. 15, 411–419 (2013).

42. Boeni, H., Silva, U. & Ott, D. E-waste recycling in Latin America: Overview, challenges and potential. Focus (Madison). 11, 1–10 (2008).

43. Menad, N., Guignot, S. & van Houwelingen, J. A. New characterization method of electrical and electronic equipment wastes (WEEE). Waste Manag. 33, 706–713 (2013).

44. Wang, F. et al. The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag. 32, 2134–2146 (2012).

45. Streicher-Porte, M. & Geering, A.-C. Opportunities and Threats of Current E-Waste Collection System in China: A Case Study from Taizhou with a Focus on Refrigerators, Washing Machines, and Televisions. Environ. Eng. Sci. 27, 29–36 (2010).

46. Lepawsky, J. The changing geography of global trade in electronic discards: Time to rethink the e-waste problem. Geogr. J. (2015). doi:10.1111/geoj.12077

47. Cui, J. & Forssberg, E. Mechanical recycling of waste electric and electronic equipment: A review. Journal of Hazardous Materials 99, 243–263 (2003).

48. Zeng, X., Mathews, J. A. & Li, J. Urban mining of E-waste is becoming more cost-effective than virgin mining. Enviornmental Sci. Technol. 52, 4835–4841 (2018).

49. Yu, J., Ju, M. & Williams, E. Waste electrical and electronic equipment recycling in China: Practices and strategies. 2009 IEEE Int. Symp. Sustain. Syst. Technol. ISSST '09 Coop. with 2009 IEEE Int. Symp. Technol. Soc. ISTAS 24, 1 (2009).

50. Oteng-Ababio, M. When necessity begets ingenuity: E-waste scavenging as a livelihood strategy in accra, Ghana. African Stud. Q. 13, 1–21 (2012).

51. Paul, J. G., Arce-Jaque, J., Ravena, N. & Villamor, S. P. Integration of the informal sector into municipal solid waste management in the Philippines - What does it need? Waste Manag. 32, 2018–2028 (2012).

52. Prakash, S. Socio-economic assessment and feasibility study on sustainable e-waste management in Ghana commissioned by the Inspectorate of the Ministry of Housing,

Spatial Planning and the Environment of the Dutch Association for the Disposal of Metal. 49, 30–40 (2010).

53. Ni, H.-G. & Zeng, E. Y. Law enforcement and global collaboration are the keys to containing e-waste tsunami in China. Environ. Sci. Technol. 43, 3991–3994 (2009).

54. Agarwal, A., Singhmar, A., Kulshrestha, M. & Mittal, A. K. Municipal solid waste recycling and associated markets in Delhi, India. Resour. Conserv. Recycl. 44, 73–90 (2005).

55. Basel Action Network. Waste tourism: is Thailand becoming the new e-waste. (2018). Available at: http://www.ban.org/news/2018/5/23/waste-tourism-is-thailand-becoming-the-new-e-waste-dumping-ground. (Accessed: 1st January 2019)

56. Heacock, M. et al. E-Waste and harm to vulnerable populations: a growing global problem. Environ. Health Perspect. 124, 550–556 (2015).

57. Amankwaa, E. F. Livelihoods in risk : exploring health and environmental implications of e-waste recycling as a livelihood strategy in Ghana *. J. Mod. Afr. Stud. 51, 551–575 (2013).

58. Grant, R. & Oteng-Ababio, M. Mapping the Invisible and Real 'African' Economy: Urban E-Waste Circuitry. Urban Geogr. 33, 1–21 (2012).

59. Umair, S., Anderber, S. & Pottig J. Informal electronic waste recycling in Pakistan. J. Solid Waste Technol. Magement 42, 222–235 (2016).

60. Brunner, P. H. & Rechberger, H. Handbook of material flow analysis: for environmental, resource, and waste engineers. (CRC Press, 2016).

61. Yedla, S. Development of a methodology for electronic waste estimation: A material flow analysis-based SYE-Waste Model. Waste Manag. Res. 34, 81–86 (2016).

62. Fiore, S., Ibanescu, D., Teodosiu, C. & Ronco, A. Improving waste electric and electronic equipment management at full-scale by using material flow analysis and life cycle assessment. Sci. Total Environ. 659, 928–939 (2018).

63. Hischier, R., Wäger, P. & Gauglhofer, J. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ. Impact Assess. Rev. 25, 525–539 (2005).

64. Steubing, B., Böni, H., Schluep, M., Silva, U. & Ludwig, C. Assessing computer waste generation in Chile using material flow analysis. Waste Manag. 30, 473–482 (2010).

65. Shinkuma, T. The flow of E-waste material in the Asian region and a reconsideration of international trade policies on E-waste. Environ. Impact Assess. Rev. 29, 25–31 (2009).

66. Nnorom, I. C. & Osibanjo, O. Electronic waste (e-waste): Material flows and management practices in Nigeria. Waste Manag. 28, 1472–1479 (2008).

67. Williams, E. & Kahhat, R. Product or Waste? Importation and End-of-Life Processing of Computers in Peru. Environ. Sci. Technol. 43, 6010–6016 (2009).

68. Reck, B. K. & Graedel, T. E. Challenges in metal recycling. Science (80-.). 337, 690–695 (2012).

69. Roquier, B., Jaboyedoff, P., Maithel, G. S. S., DuBois, B. & Jolliet, O. Socio-economic and environmental life cycle assessment of a glass bangle factory in Firozabad (India). in The Sustainability Practitioner's Guide to Social Analysis and Assessment (eds. Murray, J., Wiedmann, T. & McBain, D.) 180–197 (Common Ground Publishing, 2015).

70. Bhakar, V., Agur, A., Digalwar, A. K. & Sangwan, K. S. Life cycle assessment of CRT, LCD, and LED monitors. Procedia CIRP 29, 432–437 (2015).

71. Song, Q., Wang, Z., Li, J. & Zeng, X. Life cycle assessment of TV sets in China: A case study of the impacts of CRT monitors. Waste Manag. 32, 1926–1936 (2012).

72. Barba-Gutiérrez, Y., Adenso-Díaz, B. & Hopp, M. An analysis of some environmental consequences of European electrical and electronic waste regulation. Resour. Conserv. Recycl. 52, 481–495 (2008).

73. Pan, C.-H., Jeng, H. A. & Lai, C.-H. Biomarkers of oxidative stress in electroplating workers exposed to hexavalent chromium. J. Expo. Sci. Environ. Epidemiol. 1–8 (2017). doi:10.1038/jes.2016.85

74. Hong, J., Shi, W., Wang, Y., Chen, W. & Li, X. Life cycle assessment of electronic waste treatment. Waste Manag. 38, 357–65 (2015).

75. Arushanyan, Y., Ekener-Petersen, E. & Finnveden, G. Lessons learned - Review of LCAs for ICT products and services. Comput. Ind. 65, 211–234 (2014).

76. Rodriguez-Garcia, G. & Weil, M. Life cycle assessment in WEEE recycling. WEEE Recycling: Research, Development, and Policies (Elsevier Inc., 2016). doi:10.1016/B978-0-12-803363-0.00007-9

77. Sleeswijk, A. W., van Oers, L. F. C. M., Guinée, J. B., Struijs, J. & Huijbregts, M. A. J. Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. Sci. Total Environ. 390, 227–240 (2008).

78. Jolliet, O. et al. Impact 2002+: a new life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8, 324–330 (2003).

79. Wäger, P. A., Hischier, R. & Eugster, M. Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up. Sci. Total Environ. 409, 1746–1756 (2011).

80. Gullett, B. K. et al. Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations. J. Mater. Cycles Waste Manag. 9, 69–79 (2007).

81. Wernet, G. et al. Ecoinvent version 3. Int. J. Life Cycle Assess. 21, 1218–1230 (2016).

82. Cheewaphongphan, P., Junpen, A., Garivait, S. & Chatani, S. Emission inventory of on-road transport in Bangkok Metropolitan Region (BMR) development during 2007 to 2015 using the GAINS model. Atmosphere (Basel). 8, 1–34 (2017).

83. Stenvall, E., Tostar, S., Boldizar, A., Foreman, M. R. S. J. & Möller, K. An analysis of the composition and metal contamination of plastics from waste electrical and electronic equipment (WEEE). Waste Manag. 33, 915–922 (2013).

84. Méar, F., Yot, P., Cambon, M. & Ribes, M. The characterization of waste cathode-ray tube glass. Waste Manag. 26, 1468–1476 (2006).

85. Muller, S. et al. The application of the pedigree approach to the distributions foreseen in ecoinvent v3. Int. J. Life Cycle Assess. 21, 1327–1337 (2016).

86. Jolliet, O., Saade-Sbeih, M., Shaked, S., Jolliet, A. & Crettaz, P. Environmental Life Cycle Assessment. Journal of Bridge Engineering 18, (CRC Press, 2016).

87. Humbert, S., Margni, M., Jolliet, O. & various authors. IMPACT 2002 +: User Guide. Quantis-Sustainability counts 21, 36 (2012).

88. RIVM. LCIA: the ReCiPe model. (2018).

89. Leitão, S. M. Comparative analysis of the Life Cycle Impact Assessment methods in their application to chemical processes. 1–10 (2016).

90. World Health Organization (WHO). Health statistics and information systems. Metrics: disability-adjusted life year (DALY) Available at: https://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/.

91. Cui, J. & Forssberg, E. Characterization of shredded television scrap and implications for materials recovery. Waste Manag. 27, 415–424 (2007).

92. Kang, H. Y. & Schoenung, J. M. Economic analysis of electronic waste recycling: Modeling the cost and revenue of a materials recovery facility in California. Environ. Sci. Technol. 40, 1672–1680 (2006).

93. Wäger, P. A. & Hischier, R. Life cycle assessment of post-consumer plastics production from waste electrical and electronic equipment (WEEE) treatment residues in a Central European plastics recycling plant. Sci. Total Environ. 529, 158–167 (2015).

94. Meng, W., Wang, X., Yuan, W., Wang, J. & Song, G. The Recycling of Leaded Glass in Cathode Ray Tube (CRT). Procedia Environ. Sci. 31, 954–960 (2016).

95. Li, J., Shi, P., Shan, H. & Xie, Y. Environmental risk related to specific processes during scrap computer recycling and disposal. Environ. Technol. (United Kingdom) 33, 2547–2551 (2012).

96. Musson, S. E., Jang, Y. C., Townsend, T. G. & Chung, I. H. Characterization of lead leachability from cathode ray tubes using the Toxicity Characteristic Leaching Procedure. Environ. Sci. Technol. 34, 4376–4381 (2000).

97. Jang, Y. C. & Townsend, T. G. Leaching of lead from computer printed wire boards and cathode ray tubes by municipal solid waste landfill leachates. Environ. Sci. Technol. 37, 4778–4784 (2003).

98. Johansson, J. G. & Björklund, A. E. Reducing life cycle environmental impacts of waste electrical and electronic equipment recycling. J. Ind. Ecol. 14, 258–269 (2010).

99. Bigum, M., Brogaard, L. & Christensen, T. H. Metal recovery from high-grade WEEE: A life cycle assessment. J. Hazard. Mater. 207–208, 8–14 (2012).

100. Davis, J. M. & Garb, Y. A model for partnering with the informal e-waste industry: Rationale, principles and a case study. Resour. Conserv. Recycl. 105, 73–83 (2015).

101. United States Environmental Protection Agency. Current landscape of CRT recycling. <https://www.epa.gov/hw/cathode-ray-tubes-crts-0>. Accessed February 23, 2019.

102. Pant, D., Joshi, D., Upreti, M. K. & Kotnala, R. K. Chemical and biological extraction of metals present in E waste: A hybrid technology. Waste Manag. 32, 979–990 (2012).

Chapter 5 : Conclusions and Recommendations

5.1 Summary

This dissertation investigated impacts of informal e-waste recycling on human and environmental health. The main contributions of this dissertation to our understanding of informal e-waste recycling in the field of environmental health relate to the relative importance of potential routes of exposure, occupational exposures to, and impacts of, physical, and the impacts of informal recycling on the environment and human health. Each chapter is linked to the others through the concept of Total Worker Health (TWH).

In Chapter 2, potential exposures to metals from e-waste were measured in environmental samples as well as biomarkers for three exposure groups: community members from the study site in Thailand (non-e-waste workers), e-waste workers in Thailand, and e-waste workers in Chile. Linear regression models were run to determine which demographic variables are significant explanatory variables in log-metal concentrations for each group. The Method of Triads was employed to determine which type of sample exposure to e-waste metals. Results showed elevated concentrations of several metals, including lead, in soil, rice, and surface water samples from Thailand. This suggests that e-waste recycling activities are polluting the local environment, creating exposures for humans and the ecosystem alike. Surface wipe samples from Thailand showed no significant differences in concentration of metals between working surfaces and surfaces where food is prepared and/or consumed, while significant differences were found in Chile. This again suggests that workers and community members alike in Thailand are being exposed to e-waste metals during non-work activities. These findings were corroborated in the biomarker results, which showed higher concentrations of all metals except urinary and blood Cd in e-waste workers in Thailand compared to e-waste workers in Chile. Although mean concentrations for both occupational groups were below the BEI reference levels set by ACGIH, these findings are still concerning from a public health perspective as some metals, for example lead, have no safe limit in the body [1]. BEIs are guidelines, not standards, and represent the exposure at which experts believe there is no *unreasonable* risk of injury or disease, but do not guarantee that there is no risk of exposure or disease. Additionally, there is no reference level for metal mixtures, or mixtures of metals with other contaminants found in e-waste, that might have interaction effects. Some metal exposures in the Thai community group, including mean urinary Pb, were higher than the mean concentrations in the Chilean exposure group. This finding is particularly concerning as elevated concentrations of Pb were found in environmental samples in the community. This study only included adults; however, it can be assumed that children are also being exposed to lead, which causes permanent developmental and neurological damage [2].

The findings of Chapter 2 highlight the importance of workplace hygiene. For example, separation of food and work spaces in Chile resulted in significantly lower concentrations of metals on food surfaces. This hygiene practice may have contributed to lower ingestion of metals and accounted, in part, for the lower concentrations of biomarker metals relative to the Thailand occupational group. Using the Method of Triads, it was determined that wipe samples were the best approximation of the true exposure to e-waste metals. However, the number of tests that were eligible for use in the Method of Triads was low, and further testing is needed to substantiate these results.

In Chapter 3, physical hazards associated with informal recycling of e-waste were investigated. Survey data, hearing tests, personal noise dosimetry measurements, and videos were collected from informal e-waste workers in Thailand and in Chile. Videos were edited and enumerated using a tool to quantify frequency of tasks, tools used, use of PPE, and ergonomic stressors. Logistic regressions were run using the survey data to determine odds of injury occurrence. Poisson regressions were run using survey and video data to predict the rate of injury occurrence. The results showed that workers were not exposed to time-weighted average noise levels above the recommended exposure limit intended to prevent noise induced hearing loss (85 dBA). However, 46% of workers in Thailand and 23% in Chile showed signs of mild or worse hearing loss in their audiometric test results. In the previous six months, approximately 60% of workers in each country reported being injured at least once. Of those, 43% in Thailand and 66% in Chile reported being injured more than once during the same time frame. Results from regressions indicated that a variety of predictors were significant in predicting odds (logistic regression) or incidence rate ratio (Poisson regression) of injury, including demographic variables, tasks, PPE use, perceived noise levels, product being recycled, and tools.

These results from Chapter 3 highlight several potential areas for occupational health and safety interventions to protect worker health. Use of hearing protection may protect against impulsive noise exposures, like that experienced by frequent hammering. Improved housekeeping would reduce the number of sharp materials, like metals and broken glass, with which the workers have the potential to come into contact. Proper PPE to protect hands would reduce the number of injuries overall. Finally, consideration of ergonomic stressors in workplace design would cut down on musculoskeletal injuries.

Chapter 4 employed mixed material flow analysis and life cycle assessment methods to examine the economic and environmental impacts of informal e-waste recycling in a community in Thailand. For this chapter, four specific e-waste products were considered: washing machines, refrigerators, televisions, and fans. Data were collected on the initial and recovery masses of each material type for all four products. In addition, product flow data were collected for one neighborhood in the study site. These data were fed into a life cycle impact assessment to examine the impact of informal e-waste recycling relative to landfilling of the same products. Damages to human health, ecosystem quality, climate change, and resources were calculated for each material recovered and for each of the four products using Impact 2002+ methods [3]. A duplicate analysis was run using ReCiPe methods [4] and was included in the appendix. Results showed that recyclers were efficient in their recovery of materials, with 93% or better average recovery rates of the initial product mass. In sum, the studied village had 14 houses that engaged in e-waste recycling that collectively recycled approximately 40,000 kg of e-waste of the selected product types per month. The net value added from these products was 157,000 Thai Baht, or approximately 5,000 USD per month. The life cycle impact assessment showed that recycling of these four products by one village resulted in a net human health benefit of 0.2 DALYs avoided per month. Similarly, the damages to climate change and resources resulted in a net benefit of 60,000 kg CO_2 eq and 400,000 MJ, respectively, per month. Ecosystem damages resulted in a positive net impact of nearly 3 million PDF*m^2*yr, largely due to the improper handling and disposal of CRT glass.

The results from Chapter 4 show that informal e-waste recycling is efficient for dismantling operation. It has the potential to be an interesting alternative to formal recycling, by providing socio-economic benefits in developing countries as well as important environmental and human health benefits compared to landfilling, provided that hazardous materials, like leaded CRT glass, are properly handled and disposed of. The value added is an important source of income for the community. We found evidence that the informal sector is efficient at sorting and dismantling materials without the electricity consumption of large machinery in the formal sector; however, a more systematic comparison is needed to make this conclusion.

5.2 Future directions

A growing number of publications have contributed to our knowledge about the implications of e-waste on environmental health, but many questions remain. One issue with the existing literature is that most health-related studies at e-waste sites have been cross-sectional in nature. A longitudinal cohort study would allow for understanding of how e-waste affects public health, and specifically the long-term health impacts for e-waste workers and community members. This is particularly important as many of the diseases we might expect to see in populations exposed to chemicals from e-waste likely have long latency periods [5]. A cohort study allows the opportunity to examine the burden of health impacts from informal e-waste recycling.

The results of this dissertation suggest that interventions are needed to improve occupational health and safety in the informal sector, along with studies evaluating the effectiveness of different intervention strategies. The uptake and effectiveness of e-waste interventions depends on the consideration of the local culture, resources accessibility of vulnerable populations, and local socio-political systems.

This dissertation has demonstrated that e-waste workers are exposed to multiple types of chemicals simultaneously. Chemical mixtures can have different impacts on human health than exposure to individual chemicals [6]. Considering the variety of toxicants present in e-waste, exposure to these mixtures should be a priority research area for e-waste exposure science.

Lastly, repair has been touted as an alternative to e-waste recycling as it is more profitable, and ideally, less hazardous to human and environmental health [7]. However, repair of electronics requires training, and exposures to hazardous chemicals inside of e-waste still exists for repair workers, particularly in lead solder. More research is needed on the specific hazards associated with workers who engage in repair work to characterize exposure risks.

5.3 E-waste recycling and TWH

Total Worker Health (TWH) is a strategy developed by the National Institute of Occupational Safety and Health (NIOSH) that is comprised of policies, programs, and practices to integrate injury and illness prevention efforts within the workplace to enhance overall worker health [8]. A successful TWH program is one that integrates health prevention and health promotion to avoid occupational disease and injury, leading to favorable health and economic outcomes [9]. Health conditions previously thought to be unrelated to the workplace can be related to workplace health risks [10].

In the informal sector, particularly in places like Thailand and Chile where recycling in some places occurs inside or near the home, TWH offers a framework with which to improve both health in the work place as well as promote worker health outside of work. The World Health Organization (WHO)'s International Minimum Requirements for Health Protection in the Workplace requires housekeeping, careful design of work space, separate areas to rest, wash, and change clothes, protection from noise and vibration, and a first aid kit on premises [9]. In Thailand, we saw that failure to separate the work and living areas resulted in similar concentrations of metals in surface dust in work and food areas. A simple intervention to promote TWH in Thailand would be to create a separate area for work activities, away from the home. Similarly, workers could protect their health through increased access to PPE and training on its proper use and maintenance. Changing of clothes after work could reduce non-work exposures to metals and could additionally reduce contamination of the home, protecting children and family members. Improved housekeeping of work areas in both countries would reduce injury hazards from cuts, trips, and bruising. Conducting e-waste recycling activities indoors, or on cement or other non-permeable surfaces, would allow for control of e-waste material and prevention from metals entering the local environment. This would protect worker and community health through reduced contamination of soil, water, and agricultural products. Finally, education of informal workers on the hazards associated with different e-waste products would empower them to make decisions to protect their own health and the health of their community.

These interventions would collectively promote worker health during and after working hours. Such a program would provide economic benefits to worker through a reduction in lost worker productivity due to poor health. In addition, promoting cleaner work places would help to reduce the 7% loss in product mass seen in Chapter 4 in the MFA, allowing for additional income of these recovered materials and benefit to the environment through avoided emissions from primary materials and reduced pollution of metals. Most importantly, use of the TWH framework to develop interventions would protect worker health both inside and outside of the work place.

5.4 Public health recommendations

E-waste recycling is not a sustainable industry if the short-term economic benefits are outweighed by the long-term public health impacts. In places where informal e-waste recycling occurs, community members as well as workers are at risk of exposures to chemicals from e-waste. One recurrent theme in Chapters 2 and 4 was the prevalence of lead in the environment of the Thai community. In Chapter 2, we saw elevated concentrations of lead in water, soil, rice, and surface wipe samples. In Chapter 4, we calculated that over 6,000 kg of lead is disposed of in the unlined dump site in the community yearly. Children are especially vulnerable to exposures to lead and other toxicants as they are still developing and have a smaller mass than adults. E-waste contains a mixture of hazardous chemicals, several of which are known neurotoxicants [11]. Children living in e-waste sites in China had significantly elevated blood lead levels compared to nearby communities [11]. Children of formal e-waste workers are at risk of exposure to lead and other hazardous chemicals, too [12]. Children who live in areas where e-waste recycling occurs, or who have a parent that recycles e-waste, are in danger of permanent health consequences from exposures. Adults exposed to e-waste are at risk of changes in thyroid function, cellular functions, negative impacts on pregnancy and birth, changes in oxidative stress, and mixtures of chemicals known to be carcinogens, teratogens, mutagens, and a plethora of other known toxicological effects [3], [13], [14]. E-waste workers and their families are often from vulnerable populations, and may have lower access to health care, making exposures to e-waste all the more problematic [14]-[16].

Public health interventions designed to reduce exposures to all people, and especially children, are needed in e-waste sites. Despite global attempts to ban the illegal trade of e-waste, the informal industry is growing [17]. For this reason, public health interventions designed to improve the status quo in the informal sector must be developed alongside longer-term solutions like corporate social responsibility and end-of-life product design. One area of opportunity is the design of facilities for the proper disposal of hazardous materials, such as lead. A disposal facility or system would enable the containment of these materials rather than allowing them to enter the environment and could be a shared resource among recyclers.

Alternatively, areas where e-waste recycling occurs should focus on targeting of the most hazardous e-waste activities, rather than banning all informal recycling. For example, banning the informal recycling of certain products, such as CRT television screens, may allow space for informal workers to continue to generate income through e-waste while avoiding products with the largest health impacts. Prohibiting the burning of e-waste and cables would prevent the creation of toxic smoke plumes that endanger human and environmental health. Finally, the best-of-two-worlds scenario suggests utilizing the strengths of the informal industry (collection, sorting, preliminary manual dismantling) in partnership with the formal industry (recycling of trace materials, handling of hazardous materials, refining) [18]. Whichever solutions are implemented to protect public health, education and involvement of e-waste workers in the decision-making process is imperative to intervention success.

5.5 E-justice

Fundamentally, e-waste is an issue of environmental justice. Work is a social determinant of health, and the type of work a person engages in is determined by distribution of power and resources at different scales, including global. Informal e-waste recycling results in a disproportionate burden of harm among vulnerable populations in lower-income countries.
The export of hazardous materials found in e-waste places cost of workplace injury and disease onto workers with high-risk jobs, who may not have access to healthcare in the event of injury or disease [19]. Images of e-waste recycling in Agbogloshie Market in Accra, Ghana in popular media depict a situation where contentious government oversight, poverty, and crime rule a wasted landscape, calling for an end to the harms of informal recycling across the globe. The

story that is not told is that of failing government oversight of electronic trade in high-income countries, consumers who are outraged by the images of Agbogbloshie but who do not change their consumption habits, and larger issues that create a population of people so desperate for work that they engage in dangerous recycling activities like burning e-waste. In this context, the devastating conditions of informal recycling portrayed by the media is not a problem, but rather an inevitable symptom of something much larger- and something to which we have all contributed.

5.6 Significance

Informal e-waste recycling work is an important and emerging form of work associated with a range of potential health impacts. Individuals conducting e-waste recycling are directly exposed to a variety of occupational health hazards, including heavy metals, physical hazards (e.g. noise and musculoskeletal issues), and injuries. Members of communities where e-waste work occurs may have exposures to many of these hazards, as well – particularly in situations where e-waste recycling work is done in homes. Given that fact that thousands of individuals are involved in e-waste recycling globally, with millions of people exposed to e-waste toxicants [16], [20], research to identify health impacts of e-waste recycling, and to inform the development of appropriate interventions, is needed.

This dissertation has provided a comprehensive overview of informal e-waste recycling through three interrelated studies that individually and collectively made useful contributions to the field of informal e-waste studies. All three chapters were designed to address hazards associated with e-waste recycling and to provide information about what types of public and occupational health interventions may be most successful. The data collected in Chapter 2 regarding occupational and non-occupational exposure to metals within a community provided information that stakeholders and policy makers can use to decide how to best control the spread of e-waste pollution in communities and among community members. Chapter 3, which involved characterization of injury risks by task, method of disassembly used, type of e-waste product recycled, and other factors, yielded information that can help guide the development of appropriate injury prevention strategies among e-waste workers. Chapter 4, which applied material flow analysis and life cycle assessment methods, provided information that may improve decision analysis and inform occupational and public health e-waste recycling interventions to target the most harmful products and materials while simultaneously fulfilling the financial and health needs of e-waste workers. Finally, the collective results of all three chapters provided an investigation of multiple facets of e-waste through an environmental health lens, the results of which may allow for better decision-making to affect positive changes to protect human and environmental health while still allowing space in the solution for informal workers to exist and thrive in a more conscientious manner. The framing of these issues within the TWH context allows for understanding and decision-making that best protects workers in this informal industry, where boundaries between work and non-work life are blurred.

5.7 Conclusions

The results of this dissertation show that: 1) Increased concentrations of metals in rice, soil, and surface water in an e-waste community in Thailand may be due to informal e-waste recycling; 2) Poor workplace hygiene and failure to separate work and living spaces in Thailand may explain elevated concentrations of metals found in blood and urine; 3) Informal e-waste workers experience a high rate of injury, and the odds and incidence rate of injury are influenced by the types of tools used, tasks performed, ergonomic stressors, workplace housekeeping, and use of personal protective equipment; 4) Informal e-waste workers in Chile and Thailand were exposed to noise levels below thresholds set to protect hearing, but nevertheless experienced moderate rates of noise-induced hearing loss; 5) Informal e-waste workers are efficient at recovering material from products, and it is a profitable industry for low-income communities; 6) Informal e-waste recycling has the potential to result in a net benefit to human and environmental health in the form of avoided emissions, but can have a net damaging effect if hazardous materials are not properly handled. This work has highlighted several important areas for potential intervention design to improve the occupational, community, and environmental health of informal e-waste communities.

5.8 Bibliography

1. Centers for Disease Control and Prevention (CDC). Adult Blood Lead Epidemiology and Surveillance (ABLES). (2018). Available at: https://www.cdc.gov/niosh/topics/ables/description.html. (Accessed: 1st June 2018)
2. Chen, A., Dietrich, K. N., Huo, X. & Ho, S. M. Developmental neurotoxicants in e-waste: An emerging health concern. Environ. Health Perspect. 119, 431–438 (2011).
3. Humbert, S., Margni, M., Jolliet, O. & PRe, various authors. IMPACT 2002 +: User Guide. Quantis-Sustainability counts 21, 36 (2012).
4. RIVM. LCIA: the ReCiPe model. (2018).
5. Noel-Brune, M. et al. Health effects of exposure to e-waste. Lancet 1, e70 (2013).
6. Hernández, A. F. & Tsatsakis, A. M. Human exposure to chemical mixtures: Challenges for the integration of toxicology with epidemiology data in risk assessment. Food Chem. Toxicol. 103, 188–193 (2017).
7. Streicher-Porte, M. et al. Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi. Environ. Impact Assess. Rev. 25, 472–491 (2005).
8. Schill, A. L. & Chosewood, L. C. The NIOSH Total Worker HealthTM program: an overview. J. Occup. Environ. Med. 55, S8-11 (2013).
9. Pronk, N. P. Integrated worker health protection and promotion programs: overview and perspectives on health and economic outcomes. J. Occup. Environ. Med. 55, 612–626 (2014).
10. Centers fo Disease Control and Prevention (CDC) & National Institute for Occupational Health and Safety (NIOSH). What is Total Worker Health. Available at: https://www.cdc.gov/niosh/twh/totalhealth.html. (Accessed: 30th October 2018)

11. Huo, X. et al. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ. Health Perspect. 115, 1113–1117 (2007).

12. Ceballos, D. M. & Dong, Z. The formal electronic recycling industry: Challenges and opportunities in occupational and environmental health research. Environ. Int. 95, 157–166 (2016).

13. Frazzoli, C., Orisakwe, O. E., Dragone, R. & Mantovani, A. Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. Environ. Impact Assess. Rev. 30, 388–399 (2010).

14. Grant, K. et al. Health consequences of exposure to e-waste: a systematic review. Lancet. Glob. Heal. 1, e350-61 (2013).

15. Heacock, M. et al. E-Waste and harm to vulnerable populations: a growing global problem. Environ. Health Perspect. 124, 550–556 (2015).

16. Yu, E. A., Akormedi, M., Asampong, E., Meyer, C. G. & Fobil, J. N. Informal processing of electronic waste at Agbogbloshie, Ghana: workers' knowledge about associated health hazards and alternative livelihoods. Glob. Health Promot. 0, 1–9 (2016).

17. Baldé, C. P., Forti, V., Kuehr, R. & Stegmann, P. The global e-waste monitor - 2017. (2017).

18. Wang, F. et al. The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag. 32, 2134–2146 (2012).

19. LaDou, J. International occupational health. Int. J. Hyg. Environ. Health 206, 303–313 (2003).

20. Kishore, J. E-Waste Management : As a Challenge to Public Health in India. Network 35, 2010–2013 (2012).

Appendices

APPENDIX A:

Survey

PART 1: SURVEY INFORMATION

Interview Date: Day: ____________ Month: ____________ Year: ______________

Interview Start Time: _ _:_ _ am / pm

Interpreter Name(s) ____

PART 2: DEMOGRAPHICS

Now I will ask you some questions about yourself.

1. **What gender do you currently identify as?** ☐$_1$ Male ☐$_2$ Female ☐$_3$ Other

2. **What was your age at your last birthday?** years

3. **How long have you been living in your current residence?** years months

4. **What is your total household income per month?**
☐$_1$ Less than $50,000 ☐$_2$ $50,000-100,000 ☐$_3$ $101,000- 200,000
☐$_4$ $201,000-300,000 ☐$_5$ $301,000-500,000 ☐ $_6$ $501,000-700,000
☐ $_7$ $700,000-1,000,000 ☐ $_8$ more than $1,000,000 ☐$_{666}$ Prefer not to answer

5. **What are your household's sources of income:**

a. Agriculture?	☐$_2$Primary income source	☐$_1$Secondary income source	☐$_0$Not a source of income
b. Electric or electronic waste?	☐$_2$Primary income source	☐$_1$Secondary income source	☐$_0$Not a source of income
c. Other types of waste?	☐$_2$Primary income source	☐$_1$Secondary income source	☐$_0$Not a source of income
d. Construction/labor/mining/blue collar?	☐$_2$Primary income source	☐$_1$Secondary income source	☐$_0$Not a source of income
e. Textiles/Artisan goods?	☐$_2$Primary income source	☐$_1$Secondary income source	☐$_0$Not a source of income
f. Professional (nurse, teacher, etc)?	☐$_2$Primary income source	☐$_1$Secondary income source	☐$_0$Not a source of income
g. Other:?	☐$_2$Primary income source	☐$_1$Secondary income source	☐$_0$Not a source of income

6. **What is your marital status?**
☐$_1$ Single ☐$_2$ Married ☐$_3$ Divorced
☐$_4$ Living with partner ☐$_5$ Widowed ☐$_6$ Separated

7. How many family members (including yourself) are supported by your household's income?

8. What is the highest level of school you attended?

☐$_0$ None ☐$_1$ Basic ☐$_2$ Medium ☐$_3$Superior

PART 3: WORK HISTORY

Now I will ask you some questions about your work history.

9. Are you currently working? ☐$_1$ Yes ☐$_0$ No

10. What is/are your current job(s)? (Check all that apply)

☐$_1$ Farming/agricultural work
☐$_2$ Electronics repairer
☐$_3$ Electric or electronic waste recycling
☐$_4$ Artisan (Mason/Carpenter/Electrician/Plumber)
☐$_5$ Scrap Dealer
☐$_6$ Mechanic
☐$_7$ Shop owner/ Retailer
☐$_8$ Trading
☐$_9$ General Employee
☐$_{10}$ Electronics collection
☐$_{11}$ Food vendor
☐$_{12}$ Taxi/Minibus/Truck Driver
☐$_{13}$ Factory/industry/private section worker
☐$_{14}$ Government staff
☐$_{15}$ Retired
☐$_{16}$ Keeping house/housewife/caring for children
☐$_{17}$ School/full time study
☐$_{777}$ Other:

11. Of these jobs, which is your primary?

12. How long have you worked at your primary job? years months

13. What was your previous job? ***[Mark "none" if no previous job and skip to 16]***
14. What years did you begin and end your previous job? Start year: Stop year:

PART 4: HEALTH

Now I will ask you some questions about your health.

15. In general, my overall health is:

☐$_1$ Poor ☐$_2$ Fair ☐$_3$ Good ☐$_4$ Very Good ☐$_5$ Excellent

16. Do you have any health impairments or health problems that limit the kind or amount of work that you can do?

☐$_1$Yes ☐$_0$No

[Display if yes] **Describe:**

17. In the last two weeks, how often have you had the following conditions?

a. Skin rashes	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
b. Headache or dizziness	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
c. Shaking or tremors	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
d. Blood in your urine	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
e. Blood in your stool	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
f. Cough, shortness of breath, or difficulty breathing	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
g. Heart beating abnormally	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
h. Loose or watery stools	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
i. Fever	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently
j. Nausea or stomach ache	☐$_{1}$ Rarely or never	☐$_{2}$Occasionally	☐$_{3}$ Always or frequently

18. Have you sought medical care or treatment for <u>any</u> medical conditions?
☐$_{1}$ Yes ☐$_{0}$ No ***[Skip to 21]*** ☐$_{888}$ Don't know
[Display if yes] *Explain:*

19. Where did you seek medical treatment for the most severe of these conditions? (Select all that apply)
☐$_{789}$ N/A ☐$_{1}$ Self Medication ☐$_{2}$ Alternative Medicine
☐$_{3}$ Pharmacy ☐$_{4}$ Clinic/Hospital ☐$_{777}$ Other

20. In the past year, have you recently experienced unintentional weight loss?
☐$_{1}$ Yes ☐$_{0}$ No ☐$_{888}$ Don't know

21. Have you ever been told by a doctor or health professional that you have any of the following medical conditions?
☐$_{1}$ High Blood Pressure ☐$_{2}$ Diabetes Melitus ☐$_{3}$ Asthma
☐$_{4}$ Heart disease ☐$_{5}$ Stroke ☐$_{6}$ Kidney disease
☐$_{7}$ Liver disease ☐$_{789}$ NA/None of these ☐$_{777}$Other:

22. Are you taking medicine for any of these conditions?
☐$_{1}$ Yes ☐$_{0}$ No ☐$_{789}$ N/A ☐$_{888}$ Don't know

23. Are you pregnant now?
☐$_{789}$ N/A ☐$_{1}$ Yes ☐$_{0}$ No ☐$_{888}$ Don't know

24. Do you have any children under 21 years of age?
☐$_{1}$ Yes ☐$_{0}$ No ***[Skip to 30]***

25. How many children do you have and what are their ages?

26. In general, my child/children's overall health is:
☐$_{1}$ Poor ☐$_{2}$ Fair ☐$_{3}$ Good ☐$_{4}$ Very Good ☐$_{5}$ Excellent
☐$_{6}$ Mixed (i.e., at least one poor/fair and at least one good/excellent) ☐$_{888}$ Don't know/Unsure

27. What do you think is the greatest health problem your children currently experience?

28. In what ways, if any, do you think your job affects your children?

PART 5: STRESSORS

Now I will ask you some questions about stress in your life.

29. In the last month, how often have you felt that you were unable to control the important things in your life?

☐$_0$ Never ☐$_1$ Almost never ☐$_2$ Sometimes ☐$_3$ Fairly often ☐$_4$ Very often
☐ Prefer not to answer

30. In the last month, how often have you felt confident about your ability to handle your personal problems?

☐$_0$ Never ☐$_1$ Almost never ☐$_2$ Sometimes ☐$_3$ Fairly often ☐$_4$ Very often
☐ Prefer not to answer

31. In the last month, how often have you felt that things were going your way?

☐$_0$ Never ☐$_1$ Almost never ☐$_2$ Sometimes ☐$_3$ Fairly often ☐$_4$ Very often
☐ Prefer not to answer

32. In the last month, how often have you felt difficulties were piling up so high that you could not overcome them?

☐$_0$ Never ☐$_1$ Almost never ☐$_2$ Sometimes ☐$_3$ Fairly often ☐$_4$ Very often
☐ Prefer not to answer

33. How often does someone else decide your work methods, pace, and/or order?

☐$_1$ Rarely or never ☐$_2$Occasionally ☐$_3$ Always or frequently
☐ Prefer not to answer

34. How often do you experience violence or harassment at work?

☐$_1$ Rarely or never ☐$_2$Occasionally ☐$_3$ Always or frequently
☐ Prefer not to answer

35. How often does your work interfere with your family responsibilities or leisure time activities?

☐$_1$ Rarely or never ☐$_2$Occasionally ☐$_3$ Always or frequently
☐ Prefer not to answer

36. How often do you feel your income is not sufficient to support yourself and your family?

☐$_1$ Rarely or never ☐$_2$Occasionally ☐$_3$ Always or frequently
☐ Prefer not to answer

37. How many hours do you work in a typical week? hours

PART 6: NOISE AND HEARING

Now I will ask you some questions about noise and hearing.

The term "loud noise" here means loud enough that a person has to raise their voice to talk to someone arm's length away (about one meter)

38. How often are you exposed to loud noise at work?

☐$_0$ Never ☐$_1$ Almost never ☐$_2$ Sometimes
☐$_3$ Fairly often ☐$_4$ Very often ☐$_{888}$ Don't Know

39. How many years total have you worked in loud noise? years

40. Do you have difficulties with your hearing? ☐$_1$ Yes ☐$_0$ No

41. If yes, how long have you had difficulties with your hearing?

☐$_1$ Since birth ☐$_2$ Since childhood ☐$_3$ Since adolescence

☐$_4$ Since adulthood ☐$_{888}$ Don't Know ☐$_{789}$ N/A

42. Have you ever been told by a healthcare professional that you have hearing loss or another hearing problem?

☐$_1$ Yes ☐$_0$ No

43. After spending time in loud noise, how often do you hear ringing or whistling sounds in your ears, or does you hearing feel muffled?

☐$_0$ Never ☐$_1$ Almost never ☐$_2$ Sometimes ☐$_3$ Fairly often ☐$_4$ Very often

PART 7: OCCUPATIONAL INJURIES

Now I will ask you some questions about injuries at work.

44. How many times have you been injured while performing electronic waste recycling work in the past 6 months? times ***(If 0, Skip to 53)***

45. In the last six months, for your worst injury during electric or electronic waste recycling work, what were you doing at the time of injury?

☐$_1$ Collecting electronic waste ☐$_2$ Sorting electronic waste

☐$_3$ Removing covering of wires ☐$_4$ Dismantling Electronic Equipment

☐$_5$ Burning Activities ☐$_6$ Ash/wire collection after burning

☐$_{777}$ Other

46. In the last six months, for your worst injury during electric or electronic waste recycling work, what type of medical care did you receive?

☐$_{789}$ N/A ☐$_1$ Self Medication ☐$_2$ Alternative Medicine

☐$_3$ Pharmacy ☐$_4$ Clinic/Hospital ☐$_{777}$ Other

47. In the last six months, for your worst injury during electric or electronic waste recycling work, were you hospitalized (spent at least one night in the hospital)? ☐$_1$ Yes ☐$_0$ No

48. In the last six months, how much work did you miss due to your worst injury during electric or electronic waste recycling work?

☐$_1$ Did not miss any work and worked regular job

☐$_2$ Did not miss any work but could not do regular job

☐$_3$ Missed work: days

49. In the last six months, for your worst injury during electric or electronic waste recycling work, what body part(s) were injured? (Check all that apply)

☐$_1$ Head ☐$_2$ Eye(s) ☐$_3$ Face ☐$_4$ Mouth/teeth

☐$_5$ Neck ☐$_6$ Shoulder ☐$_7$ Arm ☐$_8$ Hand

☐$_9$ Chest ☐$_{10}$ Spine ☐$_{11}$ Waist ☐$_{12}$ Hip

☐$_{13}$ Thigh ☐$_{14}$ Knee ☐$_{15}$ Lower leg ☐$_{16}$ Ankle

☐$_{17}$ Foot ☐$_{18}$ Abdomen ☐$_{777}$ Other

50. In the last six months, for your worst injury during electric or electronic waste recycling work, what type of injury did you sustain? (Check all that apply)

☐$_1$ Contusions/abrasions ☐$_2$ Burns/scalds ☐$_3$ Concussions

☐$_4$ Cuts/lacerations ☐$_5$ Punctured wounds ☐$_6$ Amputations

☐$_{7}$ Dislocations ☐$_{8}$ Fractures (simple/compound) ☐$_{9}$ Sprains/strains
☐$_{10}$ Asphyxiation ☐$_{11}$ Internal bleeding ☐$_{12}$ Electric shock
☐$_{777}$ Other

51. In the last six months, for your worst injury during electric or electronic waste recycling work, prior to injury, had you received any instructions/training on how to avoid injury while doing your work?
☐$_{1}$ Yes ☐$_{0}$ No ☐$_{888}$ Don't know

52. Do you regularly wear any of the following safety equipment at work?

a. Safety glasses, goggles, face shields, or other eye protection?	☐$_{1}$ Yes	☐$_{0}$ No
b. Rubber-soled boots or shoes?	☐$_{1}$ Yes	☐$_{0}$ No
c. Latex or plastic gloves?	☐$_{1}$ Yes	☐$_{0}$ No
d. Leather or rubber gloves?	☐$_{1}$ Yes	☐$_{0}$ No
e. Dust mask?	☐$_{1}$ Yes	☐$_{0}$ No
f. Earplugs or earmuffs?	☐$_{1}$ Yes	☐$_{0}$ No
i. Other (please list):?	☐$_{1}$ Yes	☐$_{0}$ No

53. Are there any tools/parts of your job that lead to more frequent injuries?
☐$_{1}$ Yes ☐$_{0}$ No ☐$_{888}$ Unsure

54. *[Display if yes]* What are they?

55. Do you ever feel any pain in your hands or wrists after working with e-waste?
☐$_{1}$ Yes ☐$_{0}$ No ☐$_{888}$ Unsure
a. ***[Display if yes]* Where do you feel the pain?**
***[Display if yes]* How severe is the pain (Scale of 1-10)?**
b. ***[Display is yes]* How frequent is the pain?**

56. Do you ever feel any muscle soreness in your body from sitting in the same position for a long period of time?
☐$_{1}$ Yes ☐$_{0}$ No ☐$_{888}$ Unsure
a. ***[Display if yes]* Where do you feel the soreness?**
b. ***[Display if yes]* How severe is the muscle soreness?**
c. ***[Display is yes]* How frequent is the muscle soreness?**

57. Is there any job task that you have experienced more injuries, including minor injuries, when performing the task?
☐$_{1}$ Yes ☐$_{0}$ No ☐$_{888}$ Unsure
a. ***[Display if yes]* What job task presents the injury or risk?**
b. ***[Display if yes]* How severe is the injury?**
c. ***[Display is yes]* How frequent is the injury?**

PART 8: DIET

Now I will ask you some questions about your diet.

58. How many meals did the adults in your household eat yesterday? meals

59. How many meals did the children in your household eat yesterday? meals

60. In the past four weeks, how often was there no food of any kind to eat in your household?
☐$_{0}$ Never ☐$_{1}$ Rarely (once or twice) ☐$_{2}$Sometimes (once a week)

☐$_3$ Often (twice a week or more) ☐$_{789}$ N/A ☐$_{888}$ Don't know

61. In the past four weeks, how often did you or any member of your household go to sleep at night hungry because there was not enough food?

☐$_0$ Never ☐$_1$ Rarely (once or twice) ☐$_2$Sometimes (once a week)
☐$_3$ Often (twice a week or more) ☐$_{789}$ N/A ☐$_{888}$ Don't know

62. In the past four weeks, how often did your household not have enough food to eat?

☐$_0$ Never ☐$_1$ Rarely (once or twice) ☐$_2$Sometimes (once a week)
☐$_3$ Often (twice a week or more) ☐$_{789}$ N/A ☐$_{888}$ Don't know

PART 9: ELECTRIC AND ELECTRONIC WASTE

Now I will ask you some questions related to your work with electric or electronic waste.

63. Have you ever been involved in electric or electronic waste activities? ☐$_1$ Yes ☐$_0$ No
[Skip to 137]

64. Are you currently involved in electric or electronic waste activities? ☐$_1$ Yes ☐$_0$ No
[Display a-c if no, then skip to 74]

a. How long did you work in electric or electronic waste? years
b. How long ago did you stop working in electric or electronic waste? years
c. Why did you stop working in electric or electronic waste?

65. How long have you been working with electric or electronic waste? years

66. How long do you typically work in one day? hours

67. How many days per week do you work? days

68. How many breaks do you take during days that you work?

69. How long is a typical break? minutes

70. Do you typically work the same number of hours every week throughout the year?
☐$_1$ Yes ☐$_0$ No

71. Is electric or electronic waste recycling your main source of income? ☐$_1$ Yes ☐$_0$ No

72. What are your other sources of income?

73. Why did you choose to recycle e-waste?

74. How did you hear about working with electric or electronic waste?

75. How do you feel about working with electric or electronic waste?

76. How many different types of products have you recycled/look for?

77. What are the different types of products that you have recycled/look for?

78. What electronic products do you normally recycle/look for (products, subassemblies, components) the most?

79. At what point do you stop working on your product/subassembly?

80. What form do you pass the product on in (raw material, component, subassembly)?

81. What are your alternatives for income (other types of electric or electronic waste, other types of work)?

82. How has that time been split between the different products/roles you have taken on? (*For example, 20% of your time working with televisions, and 80% working with household appliances/white goods)*

83. With which electric or electronic waste recycling tasks are you the most familiar?

84. Do you know the new Producer's Extended Responsibility law (REP)? ☐$_1$ Yes ☐$_0$ No

85. [Display if "Yes"] What do you think of the new REP law?

86. [Display if "No"] Have you considered signing up?

87. How do you consider your work to be involved in environmental care?

88. What is your role in recycling electric or electronic waste? Do you…

a. Go out to find products to bring back to recycle? [COLLECTORS]

☐$_1$ Yes ***[Display Part 10]*** ☐$_0$ No

b. Disassemble and break down the materials? [RECYCLERS]

☐$_1$ Yes ***[Display Part 11]*** ☐$_0$ No

c. Repair electronics and resell them? [REPAIR SHOP]

☐$_1$ Yes ***[Display Part 12]*** ☐$_0$ No

d. Operate within a company that purchases raw materials? [RAW MATERIALS BUYER]

☐$_1$ Yes ***[Display Part 13]*** ☐$_0$ No

Part 10: Collector Questions

89. What electric or electronic products do you look for?

90. Why do you choose to look for these electric or electronic products?

91. Could you switch the electric or electronic products you get? ☐$_1$ Yes ☐$_0$ No

a. ***[Display if yes]*** How?

b. Why or why not?

92. How much electric or electronic waste do you usually bring to your community? ☐ Units ☐ Kilograms

a. How often?

b. How do you choose your amounts?

93. Do you know of other collectors who collect more or less electric or electronic waste than you?

☐$_1$ Yes ☐$_0$ No

a. ***[Display if yes]*** Why do they collect the amounts they do?

94. Could you increase or decrease your amounts whenever you want? ☐$_1$ Yes ☐$_0$ No

95. When you have a technical problem (for example, how to transport e-waste to your location), who do you go to ask?

a. Why?

96. Where do you get your electric or electronic products from?

a. Why?

b. Do you pay to take these products? ☐$_1$ Yes ☐$_0$ No

c. *[Display if yes to b]* How much do you pay? ☐Per unit ☐Per week ☐Per month
d. Do you ever change where you get the products from? ☐$_1$ Yes ☐$_0$ No
e. Why or why not?

97. Where do you bring your electric or electronic products to?
a. Why?
b. How did you decide who to distribute to?
c. How did you establish these relationships/connections?
d. Do you get money for the products? ☐$_1$ Yes ☐$_0$ No
e. *[Display if yes to d]* How much?
f. *[Display if yes to d]* Why?
g. Who gets the products from there (if a pickup location)?
h. How did you find out about this method of selling it?
i. What do the buyers do with it?
j. Do you keep any products for your own home to recycle? ☐$_1$ Yes ☐$_0$ No
k. *[Display if yes to j]* How do you decide what to keep?

98. Do you consider it beneficial to partner with other collectors and marketers, for example, in cooperatives?
☐$_1$ Yes ☐$_0$ No

99. When you have a problem with your work, who do you go to ask?
a. Why do you go to that person?

Part 11: Recycler Questions

100.Do you ever recycle TVs or computers? ☐$_1$ Yes ☐$_0$ No

101.How did you choose these products to work with/recycle?
a. What characteristics do you look for?
b. Why?
c. What is the process if you wanted to switch e-waste items (i.e. recycle fans instead of TVs)?
d. How many TVs/computers do you recycle per week? units
e. How much time does it take one recycler to complete their work on a TV/computer?
f. How much does a TV/computer weigh before recycling begins?
g. Does one recycler process the entire item, or is there a division of tasks per item?
☐$_1$ One recycler ☐$_0$ Division of tasks
h. *[Display if 'Division of tasks' selected in g]* How is the division of tasks organized?

102.What primary materials are the product(s) made out of (for example, plastic, aluminum, printed circuit board, steel)?
a. Which are important to you?
b. What do you do with them?
c. How much of each material (raw material) do you recover per TV/computer? % of total material
d. Do you sell any components? ☐$_1$ Yes ☐$_0$ No
e. *[Display if yes to d]* If so, to who?
f. *[Display if yes to d]* What do they do with it?
g. What parts are you unable to sell/recycle?
h. What do you do with these parts?

103.Do you work with anyone else to recycle product(s)? ☐$_1$ Yes ☐$_0$ No [***Skip to 103***]
a. Who?

b. Why?
c. Where?
d. Do you hire anyone else or do you work for somebody?
☐$_1$ Hire someone else ☐$_0$ Work for somebody
e. Why?
f. If you are an employee, who pays you?
g. How are your paid? ☐$_0$ Per hour ☐$_1$ Per unit ☐$_2$ Per day ☐$_3$ Other
h. How much are you paid? Chilean Pesos

104. Can you walk me through an overview of the process each of you go through?
a. How much time does each task take? ☐$_0$Hours ☐$_1$Days ☐$_2$Weeks
b. How many tasks do you have?
c. How many tasks do the others have?
d. How are the tasks split?
e. Does everyone do the same task for all the same product/subassembly?
☐$_1$ Yes ☐$_0$ No
f. How was this decided?
g. Why?
h. Could you switch your task to something else? ☐$_1$ Yes ☐$_0$ No
i. Why or why not?

105. What methods do you use to carry out each task?
a. Why do you use these methods?
b. Did you learn any techniques or tips from others? ☐$_1$ Yes ☐$_0$ No
c. ***[Display if yes to b]*** Who did you learn from?
d. ***[Display if yes to b]*** What were the methods you learned from others?

106. How much time does it usually take from when the product/subassembly arrives to when the end product leaves? ☐$_0$Hours ☐$_1$Days ☐$_2$Weeks
a. Why does it take this long?

107. How do you know when to stop working on it and move it onto the next person?
a. What does the product look like when it leaves your hands?
b. How was this decided?
c. What do you do with the rest of the waste product parts?

108. What tools do you use to do each task?
a. Could you use something else? ☐$_1$ Yes ☐$_0$ No
b. ***[Display if yes to a]*** What else could you use?
c. Why did you choose these tools?

109. Where do you store the e-waste when you haven't worked on it yet?
a. Why do you store it in that location?

110. Where do you do each of your disassembly/recycling tasks?
a. Why?
b. Is it inside or outside? ☐$_1$ Inside ☐$_0$ Outside

111. Where do you store the waste after you have worked on it / finished with it?
a. Why?

112. When you have a problem with your work, who do you go to ask?
a. Why do you go to that person?

113. Where do you usually get your food from?

a. Is food cooked in the kitchen often? ☐1 Yes ☐0 No

b. How far is the kitchen from e-waste recycling work or storage? meters

Part 12: Repair Shop Questions

114. When you have a problem with the shop, who do you go to ask?

a. Why do you go to that person?

115. How do you get electric or electronic products?

116. How did you choose to get the product this way?

117. How much do you pay for the products (include units, e.g., pesos/unit or pesos/kg)?

118. What do you with the electric or electronic product after you work on it?

a. Do you give it to someone or sell it to someone?

☐1 Give it ☐2 Sell it ☐3 Both

b. Who do you give it to?

c. Who do you sell it to?

d. How did you choose who to pass it on to?

e. Do you go to one person/shop more often than the others? ☐1 Yes ☐0 No

f. Could you switch to another person or shop? ☐1 Yes ☐0 No

g. Why or why not?

h. Where do you sell it?

i. How much do you sell it for?

j. Why do you sell it for that much?

k. How did you find out about this method of selling it?

l. What do the buyers do with it?

Part 13: Raw Materials Buyer - Company

119. How many people work in your shop?

120. What are their different roles?

121. What types of products/materials do you receive?

122. How much do you buy the materials listed in question 118 for?

123. How are these buying prices determined?

124. How many kgs of each material do you buy per month?

125. Who do you sell the recyclable materials to?

126. How did you decide to sell to the company(ies) in question 122?

127. Could you change who you sell to?

128. How much do you sell the materials for?

129. How are these selling prices determined?

130. How many kgs of these materials do you sell per month?

131. Why do you accept these materials?

132. What do you look for when receiving these materials?

133. Who brings materials to you?

134. How do people know to bring materials to you?

135. Do you do business with the same people or do people choose to recycle at multiple shops?

136. Why do people come to you over other places to sell their materials?

137. How do you sort the materials?

PART 14: TOBACCO AND ALCOHOL USE

Now I will ask you some questions about your tobacco and alcohol use.

138. Have you smoked at least 100 cigarettes during your entire life (equivalent to about 5 packs)?
☐$_1$ Yes ☐$_0$ No ☐$_{888}$ Don't know ☐$_{999}$ Prefer not to answer

139. Do you smoke cigarettes now?
☐$_1$ Yes ☐$_0$ No ☐$_{888}$ Don't know ☐$_{999}$ Prefer not to answer

a. ***[Display if yes]*** **How many days do you smoke per week?** days
b. ***[Display if yes]*** **How many cigarettes do you smoke per day?** cigarettes
c. ***[Display if yes]*** **How long have you been smoking?** years

140. Do you ever smoke inside the house?
☐$_1$ Yes ☐$_0$ No ☐$_{789}$ N/A ☐$_{999}$ Prefer not to answer

141. Are you often around people who smoke?
☐$_1$ Yes ☐$_0$ No ☐$_{888}$ Don't know ☐$_{999}$ Prefer not to answer

142. Compared to yourself, how often do your family/friends/co-workers smoke cigarettes?
☐$_1$ Much more than me ☐$_2$ A little more than me ☐$_3$ About the same as me
☐$_4$ A little less than me ☐$_5$ Much less than me ☐$_{888}$ Don't know/Unsure
☐$_{999}$ Prefer not to answer

143. On average, how many days per week do you think your friends and co-workers consume alcohol?
☐$_0$ Never ☐$_1$ 1-3 days ☐$_2$ 4-6 days ☐$_3$ Daily
☐$_{888}$ Don't Know ☐$_{999}$ Prefer not to answer

144. In the past month on the days when your friends/co-workers drank, on average, how many drinks do you think they consumed? [A drink= 1 beer, 1 shot of liquor, 1 glass of wine]
Drinks ☐$_{888}$ Don't Know ☐$_{789}$ N/A ☐$_{999}$ Prefer not to answer

143. Interview Stop Time: : am / pm

Thank you for your time!

APPENDIX B:

Additional tables from Chapter 2

Table B-1 Regression coefficients for log Blood Cd concentration in Chile occupational exposure group (n=71).

	Model 1				Model 2				Model 3			
Variable	**β**	**SE**	***β***	**p**	**β**	**SE**	***β***	**p**	**β**	**SE**	***β***	**p**
Constant	1.162	0.505		0.025	1.150	0.501		0.025	1.156	0.343		0.001
Over Min Wage	-0.388	0.119	-0.375	0.002	-0.393	0.118	-0.380	0.001	-0.410	0.113	-0.396	0.001
Education – 1º	-1.027	0.350	-1.008	0.005	-1.009	0.343	-0.991	0.005	-1.009	0.337	-0.990	0.004
Education – 2º	-0.908	0.352	-0.835	0.012	-0.892	0.346	-0.821	0.012	-0.897	0.341	-0.825	0.011
Education - SC	-0.798	0.374	-0.522	0.037	-0.791	0.371	-0.517	0.037	-0.790	0.364	-0.516	0.034
Age	0.003	0.004	0.072	0.547	0.002	0.004	0.059	0.599				
BMI	-0.005	0.010	-0.573	0.635	-0.004	0.009	-0.043	0.703				
Sex – Female	0.046	0.137	0.042	0.739								
Adj. R^2	0.166				0.177				0.197			

C = college.

Table B-2 Regression coefficients for log urinary Cd concentrations among Chile occupational exposure group (n=68).

Variable	Model 1 β	SE	*β*	p	Model 2 β	SE	*β*	p	Model 3 β	SE	*β*	p
Constant	0.533	0.167		<0.001	0.356	0.140		0.014	0.533	0.168		0.002
Over Min Wage	-0.168	0.039	-0.477	<0.001	-0.150	0.039	-3.80	<0.001	-0.123	0.041	-0.350	0.004
Education – 1º	-0.204	0.115	-0.587	0.082	-0.194	0.113	-0.557	0.091	-0.221	0.112	-0.636	0.052
Education – 2º	-0.185	0.117	-0.493	0.118	-0.175	0.114	-0.466	0.131	-0.202	0.113	-0.539	0.078
Education - C	-0.171	0.124	-0.335	0.171	-0.158	0.121	-0.309	0.196	-0.177	0.119	-0.347	0.141
Sex – Female	0.076	0.042	0.198	0.079	0.096	0.043	0.252	0.028	0.125	0.045	0.327	0.007
Age					0.003	0.001	0.223	0.053	0.004	0.002	0.309	0.013
BMI									-0.008	0.004	-0.225	0.069
Adj. R^2	0.208				0.243				0.272			

Table B-3 Regression coefficients for log blood Mn concentrations among Thailand community exposure group (n=27).

Variable	Model 1 β	SE	*β*	p	Model 2 β	SE	*β*	p	Model 3 β	SE	*β*	p
Constant	1.508	1.293		0.257	1.033	0.792		0.206	0.990	0.776		0.215
Sex – Female	0.812	0.365	0.455	0.037	0.889	0.321	0.498	0.011	0.870	0.314	0.487	0.011
BMI	0.029	0.032	0.170	0.370	0.028	0.031	0.164	0.378	0.031	0.030	0.184	0.305
Education – 2º	-0.254	0.258	-0.188	0.336	-0.224	0.246	-0.166	0.371	-0.200	0.237	-0.148	0.409
Over Min Wage	0.153	0.276	0.106	0.584	0.143	0.270	0.099	0.602				
Age	-0.008	0.178	-0.098	0.643								
Adj R^2	0.149				0.179				0.205			

Table B-4 Regression coefficients for log urine Mn concentrations among Thailand community exposure group (n=27).

Variable	Model 1 β	SE	*β*	p	Model 2 β	SE	*β*	p	Model 3 β	SE	*β*	p
Constant	4.645	5.346		0.395	3.442	3.027		0.268	2.816	2.92		0.345
BMI	-0.123	0.134	-0.191	0.368	-0.128	0.128	-0.199	0.328	-0.097	0.122	-0.151	0.435
Education – 2º	-2.266	1.083	-0.443	0.049	-2.188	1.015	-0.428	0.042	-1.947	0.971	-0.381	0.057
Over Min Wage	1.153	1.300	0.193	0.385	1.068	1.123	0.179	0.396				
Sex – Female	0.264	1.533	0.039	0.865								
Age	-0.030	0.074	-0.093	0.68								
Adj R^2	0.015				0.090				0.100			

Table B-5 Regression coefficients for log urine Zn concentrations among Thailand community exposure group (n=26).

	Model 1				**Model 2**				**Model 3**			
Variable	**β**	**SE**	***β***	**p**	**β**	**SE**	***β***	**p**	**β**	**SE**	***β***	**p**
Constant	4.851	1.887		0.018	4.931	1.124		<0.001	6.062	0.461		<0.001
Education – 2º	-1.013	0.376	-0.524	0.014	-0.991	0.344	-0.513	0.008	-1.151	0.542	-0.548	<0.001
Sex – Female	-0.294	0.533	-0.115	0.588	-0.338	0.455	-0.132	0.465	-0.558	0.515	-0.150	<0.001
BMI	0.026	0.046	0.105	0.584	0.030	0.043	0.124	0.493				
Over Min Wage	0.170	0.402	0.082	0.678								
Age	0.002	0.026	0.019	0.929								
Adj. R^2	0.115							0.185	0.298			

Table B-6 Spearman correlation coefficient between blood or serum and urine samples by exposure group.

Samples	**Group**	**n**	**Cd**	**Cu**	**Fe**	**Pb**	**Mn**	**Ni**	**Zn**
B/S*U	0	42	0.108	0.193	0.453	0.632	-0.100	0.334	0.626
	1	103	NA	0.010	-0.189	0.178	-0.171	0.038	0.152
	2	82	0.176	NA	NA	0.362	-0.140	NA	NA
B/S*FW	0	17	NA	0.553	0.184	NA	0.051	-0.200	0.048
	1	33	NA	-0.336	0.031	NA	-0.284	NA	0.152
	2	38	NA	NA	NA	-0.081	0.012	NA	NA
B/S*WW	0	15	NA	0.218	-0.534	-0.143	0.238	0.252	0.030
	1	29	NA	-0.186	-0.346	-0.220	0.048	-0.249	0.010
	2	37	NA	NA	NA	-0.135	-0.007	NA	NA
U*FW	0	17	NA	0.255	-0.057	NA	0.255	-0.332	0.017
	1	38	NA	0.175	0.088	NA	0.001	NA	-0.015
	2	36	NA	0.049	0.441	0.187	0.052	NA	-0.151
U*WW	0	15	NA	0.470	0.226	-0.184	-0.044	-0.042	0.300
	1	34	NA	0.023	-0.221	-0.304	0.203	-0.217	0.010
	2	35	NA	-0.007	0.043	-0.043	0.002	-0.144	0.204
FW*WW	0	8	NA	0.284	0.992	0.473	-0.284	0.284	0.661
	1	39	NA	-0.203	-0.013	0.273	0.042	NA	-0.165
	2	38	NA	0.231	-0.111	0.281	0.012	NA	-0.411
AA*FW	0	7	NA	NA	-0.261	NA	NA	NA	-0.500
	1	2	NA	NA	NA	NA	NA	NA	NA
	2	21	NA	NA	-0.473	NA	NA	NA	-0.287
AA*WW	0	6	NA	NA	0.870	NA	NA	NA	NA
	1	2	NA	NA	NA	NA	NA	NA	NA
	2	21	NA	NA	0.242	NA	NA	NA	0.015
AA*B	0	10	NA	NA	0.107	NA	NA	NA	0.095
	1	4	NA	NA	-0.200	NA	NA	NA	-0.316
	2	NA	NA	NA	NA	NA	NA	NA	NA
AA*U	0	10	NA	NA	0.142	NA	NA	NA	0.057
	1	7	NA	NA	-0.464	NA	NA	NA	0.259
	2	29	NA	NA	-0.028	NA	NA	NA	0.032
PA*FW	1	22	NA	NA	-0.064	NA	NA	NA	NA
PA*WW	1	20	NA	NA	0.038	NA	NA	NA	NA
PA*B	1	25	NA	NA	-0.017	NA	NA	NA	NA
PA*U	1	27	NA	NA	0.127	NA	NA	NA	NA
% pos ρ[1]			100	78.6	50.0	50.0	61.1	40.0	69.6

NA indicates that one or more variables did not meet the assumptions for the Pearson correlation test. PA, personal air sample; AA, area air sample; WW, work surface wipe sample; FW, food surface wipe sample; B, blood biomarker; S, serum biomarker; U, urine biomarker. [1]% of positive Spearman ρ within a metal type.

APPENDIX C:

Semi-Quantitative Video Hazard Analysis Tool

Hazard Type	Attribute, Item	Frequency				
		Never	Occasional	Frequent	Always	Undetermined
Mechanical	Hand tools					
	Sharp blade					
	Blunt striking instrument					
	Screw driver					
	T-wrench					
	Wrench					
	Pliers/scissors					
	Bolt cutters					
	Power tools					
	Power drill					
	Power Saw					
	Angle grinder					
Musculoskeletal	Repetitive hand motion					
	Repetitive arm motion					
	Constant hand grip					
	Lifting > 20 pounds					
	Lifting < 20 pounds					
	Bending					
	Back					
	Neck					
	Squatting or kneeling					
	Sitting low to ground					
	Pushing or pulling					
Chemicals	Use of chemicals					
Lacerations	Breaking glass					
	Handling broken glass					
	Collecting broken glass					
	Working near broken glass					
	Working near sharp metal					
	Removing sharp metal					
	Handling/moving sharp metal					
	Cutting					
Burns	Soldering					
	Burning e-waste					
Noise	Noisy activities					
PPE	Must be wearing					
	Cotton Gloves					
	Latex gloves					
	Close-toed shoes					
	Dust mask					
	Fabric as mask					
	Respirator					

	Long sleeves					
	Long pants					
	Hearing protection					

APPENDIX D:

Mass Balances for Individual Products

Table D-1 Mass balance of washing machines in kg.

Make and model	Starting mass	Steel	Copper	Aluminum	Cables	Plastic	Waste	Sum	Change
	Kg								
PAL PC650- Alpha	16.4	5.2	0.6	0.0	0.1	10.2	0.01	16.0	2.3
Peacock PW 57	17.4	4.1	0.0[3]	0.4	0.2	11.8	0.0	16.6	4.64
Samsung SW-458	22.8[2]	13.1	0.9	0.3	0.3	7.6	0.0	22.82	N/A
Kia 105	21.0	5.6	0.7	0.1	0.4	14.0	0.1	20.8	1.1
Toshiba VH-1250ST	32.9	14.7	1.1	0.2	0.5	15.4	0.2	32.1	2.6
N/A[1]	19.6	8.1	0.4	0.0	0.3	10.9	0.0	19.7	-0.3
Average	18.3	8.5	0.7	0.2	0.3	11.8	0.1	21.2	1.7
SD	2.4	4.4	0.3	0.2	0.1	2.8	0.1	5.8	1.8

[1]Label eroded; make and model not identifiable.
[2]Starting weight unavailable due to lack of field assistance to weigh starting product, so starting mass set equal to weight of recovered materials. This product not included in average calculations for starting weight or % difference.
[3]There was no copper in this product; wiring in the motor used aluminum instead of copper.

Table D-2 Mass balance of refrigerators in kg.

Make and model	Starting mass	Steel	Copper	Aluminum	Cables	Plastic	Waste	Sum	Change
	Kg								
Sanya PB 1978B	31.5	16.1	0.8[3]	1.2	0.6	4.0	2.7	25.4	19.4[4]
Hatachi R-17DP	33.5	19.6	0.9[3]	1.0	0.6	7.0	4.2	33.2	0.8
National[1]	32.5[2]	20.8	0.9[3]	0.9	0.4	3.0	2.1	28.1	0.0
Toshiba[1]	31.0	20.3	1.1	0.9	0.9	4.2	4.1	31.5	-1.5
N/A[1]	34.1	19.7	0.9[3]	1.1	1.0	6.4	4.2	33.2	2.7
Average	32.5	19.3	1.5[3]	1.0	0.7	4.9	3.5	30.3	4.3
SD	1.5	1.9	0.3	0.1	0.2	1.7	1.0	3.4	8.6

[1]Label eroded; make and/or model not identifiable.
[2]Starting weight estimated based on median of other refrigerator weights.
[3]Estimated based on average copper composition of 3 recycled compressors (data not shown) using individual product compressor weight (data not shown).
[4]The large % change is due in part to the failure of recycler to recover materials.

Table D-3 Mass balance of televisions in kg.

Make and model	Starting mass	Steel	Copper	Aluminum	Cables	Plastic	PCB	CRT	Waste	Sum	% Change
	Kg										
Distar DT-2116AY	21.0	2.3	0.2	0.1	0.04	4.0	1.2	13.2	0.0	21.0	0.1[2]
National[1]	19.0	1.3	0.2	0	0.2	3.8	1.2	12.0	0.3	19.0	-0.1
Sony[1]	24.0	3.2	0.3	0	0.5	3.2	1.0	14.5	0.1	22.8	5.1
SHARP[1]	22.0	2.5	0.3	0	0.3	3.8	1.0	13.8	0.3	22.0	0.1
SHARP[1]	21.6	2.2	0.2	0	0.2	3.6	0.8	13.8	0.3	21.2	1.8
Average	21.5	2.3	0.2	NA	0.3	3.7	1.0	13.3	0.2	21.2	1.4
SD	1.8	0.7	0.1	NA	0.2	0.3	0.2	1.8	0.1	1.4	2.2

[1]Label eroded; make and/or model not identifiable.
[2]Calculated using non-rounded values.

Table D-4 Mass balance of fans in kg.

Make and model	Starting mass	Steel	Copper	Aluminum	Cables	Plastic	Waste	Sum	% Change
	Kg								
Mitsubishi1	3.3	1.6	0.2	0.3	0.1	0.4	0.2	2.8	14.9
Tefal VU3520	2.8	1.1	0.2	0.2	0.1	1.0	0.0	2.6	7.3
N/A[1]	2.0	0.9	0.1	0.0	0.1	0.7	0.1	2.0	2.3
N/A[1]	3.8	1.9	0.2	0.1	0.1	1.1	0.3	3.7	1.6
Average	3.0	1.4	0.2	0.2	0.1	0.8	0.2	2.8	6.5
SD	0.8	0.4	0.1	0.1	0.02	0.3	0.1	0.7	6.1

[1]Label eroded; model not identifiable.

APPENDIX E:

Life Cycle Inventory

Table E-1 Life cycle inventory processes for recycled e-waste materials and processes.

Inventory	Amount	Process
Steel		
Avoided products per 1.12 kg recycled	1.0 kg	Steel, low-alloyed {GLO}| market for | Cut-off, U
Inputs from technosphere	1.0 kg	Steel, low-alloyed {RER}| steel production, electric, low-alloyed | Cut-off, U, adjusted for removal of input flow of 1.1209 kg iron scrap, sorted, pressed.
	582.4 kgkm	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO3| Cut-off, S adapted for Thailand using ratio of EURO2 emissions where possible.
Copper		
Avoided products per 1.31 kg recycled	1.0 kg	Copper {RoW}| production, primary | Cut-off, U
Inputs from technosphere	1.0 kg	Copper {RER}| treatment of scrap by electrolytic refining | Cut-off, U, adjusted for removal of input flow of 1.31 kg of copper scrap, sorted, pressed.
	681.2 kgkm	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO3| Cut-off, S adapted for Thailand using ratio of EURO2 emissions where possible.
Aluminum		
Avoided products per 1.009 kg recycled	1.0 kg	Aluminum, primary, ingot (IAI Area, Russia & RER w/o EU27 & EFTA)| aluminum production, primary, ingot |Cut-off, U
Inputs from technosphere	1.0 kg	Aluminum, wrought alloy {RoW}| treatment of aluminum scrap, post-consumer, prepared for recycling, at remelter |Cut-off, U, adjusted for removal of input flow of 1.009 kg of aluminum scrap, post-consumer, prepared for melting.
	524.7 kgkm	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO3| Cut-off, S adapted for Thailand using ratio of EURO2 emissions where possible.
Plastic		
Avoided products per X kg recycled	N/A	N/A: Industry secret
Inputs from technosphere	0.42 kg	Acrylonitrile-butadiene-styrene copolymer {RoW}| production | Cut-off, U
	0.20 kg	Polypropylene, Granulate {GLO}| market for | Cut-off, U
	0.28 kg	Polystyrene, high impact {GLO}| market for | Cut-off, U
	N/A	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO3| Cut-off, S (weight is industry secret)

Table continued on next page…

Table E-1 (Continued).

Inventory	Amount	Process
Cables		
Avoided products per 1.31 kg recycled	0.675 kg	Copper {RoW}| production, primary | Cut-off, U
Inputs from technosphere	1.0 kg	Copper {RER}| treatment of scrap by electrolytic refining | Cut-off, U, adjusted for removal of input flow of 1.31 kg of copper scrap, sorted, pressed.
	351 kgkm	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO3| Cut-off, S adapted for Thailand using ratio of EURO2 emissions where possible.
Emissions/air	5000 ng	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-
	140 mg	Antimony
	171 mg	Bromine
	785 mg	Chlorine
	106 mg	Copper
	964 mg	Lead
	25.6 mg	Potassium
	42.9 mg	Sodium
	3.02 mg	Sulfur
	81.2 mg	Tin
	98.2 mg	Zinc
	0.4496 kg	Carbon dioxide, fossil
	17,500 mg	Particulates
PCB		
Avoided products per 2.7228 kg recycled	0.0016 kg	Gold {RoW} production | Cut-off, U
	0.0029 kg	Palladium {RU}| platinum group metal mine operation, ore with high content| Cut-off, U
	0.0945 kg	Silver {RoW}| gold-silver mine operation with refinery | Cut-off, U
Inputs from technosphere	0.00095 kg	Silver {SE}| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Cut-off, U, adapted by deleting input flows of blister copper processes from the inputs for this process.
	0.0016 kg	Gold {SE}| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Cut-off, U, adapted by deleting input flows of blister copper processes from the inputs for this process.
	0.0028 kg	Palladium {SE}| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Cut-off, U, adapted by deleting input flows of blister copper processes from the inputs for this process.
	1420 kgkm	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RoW}| transport, freight, lorry 3.5-7.5 metric ton, EURO3| Cut-off, S adapted for Thailand using ratio of EURO2 emissions where possible.
Outputs to technosphere	2.7228 kg	Used printed wiring boards {CA-QC}| treatment of scrap printed wiring boards, shredding and separation | Cut-off, U
CRT		
Inputs from technosphere	1.0 kg	Glass cullet, lead containing, from used cathode ray tube {GLO}| treatment of, 0% water, inert material landfill | Cut-off, U
Emissions to soil	0.06905 kg	Lead

APPENDIX F:

LCA Impact 2002+ Supplementary Materials

F.1 Tool use calculations and LCA results

Table F-1 LCA inputs for tools used by informal e-waste recyclers.

Tool	Process	Mass for process (kg)	Life time
Drill			5 years
Nylon plastic	(injection moulding)	0.454	
Steel, unalloyed	production	1.701	
Steel	processing	1.701	
PVC	production	0.032	
PVC	processing	0.032	
Copper	production	0.082	
Copper	processing	0.082	
Hammer			1 year
Steel	production	0.464	
Steel	processing	0.464	
Fiberglass	production & processing	0.072	
Pliers		0.272	1 year
Steel	production	0.272	
Steel	processing	0.272	

Table F-2 Calculations for average tool use per product based on tool life time and average number of products per month.

Item	Avg item/mo	Avg item/year	Avg Drill/item	Avg Hammer/item	Avg Pliers/item
Television	46	552	0.0004	0.0018	0.0018
Fan	92	1104	0.0002	0.0009	0.0009
Washing machine	33	396	0.0005	0.0025	0.0025
Refrigerator	35	420	0.0005	0.0024	0.0024

Table F-3 Calculations showing average drill use time and electricity consumption per product type.

Item	Time (s)	Time (h)	Watts	Wh	kWh/product piece
Television	90	0.025	700	17.5	0.0175
Fan	150	0.042	700	29.167	0.029
Washing machine	30	0.008	700	5.833	0.006
Refrigerator	30	0.008	700	5.833	0.006

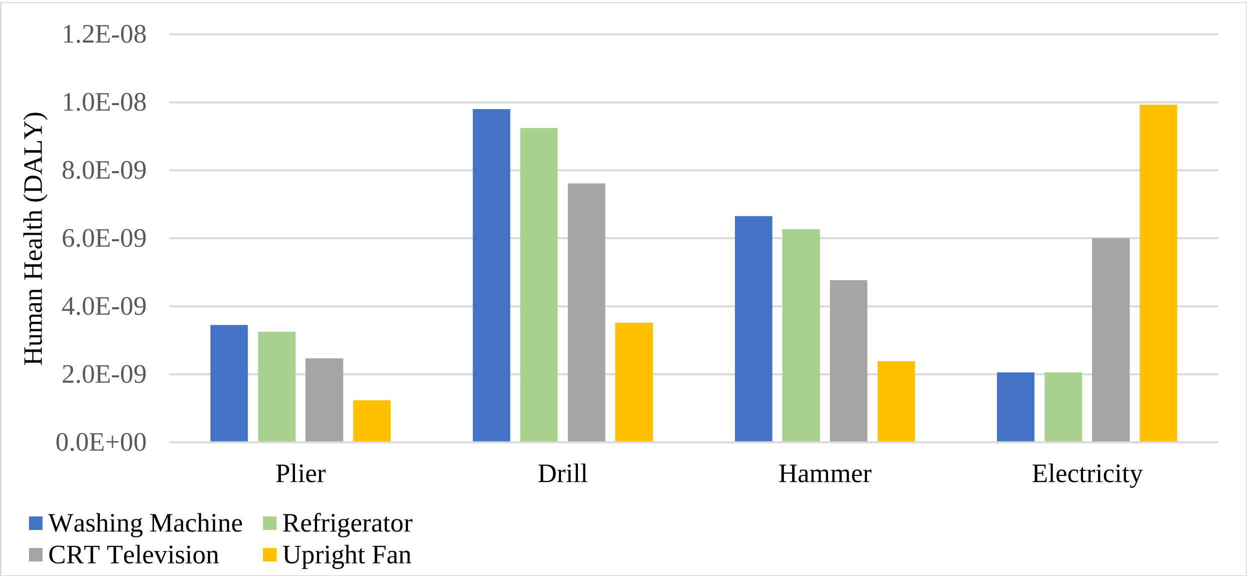


Figure F-1 Human health (DALY) endpoint damages in informal e-waste recycling by tool type per recycled product piece for four product types using Impact 2002+.

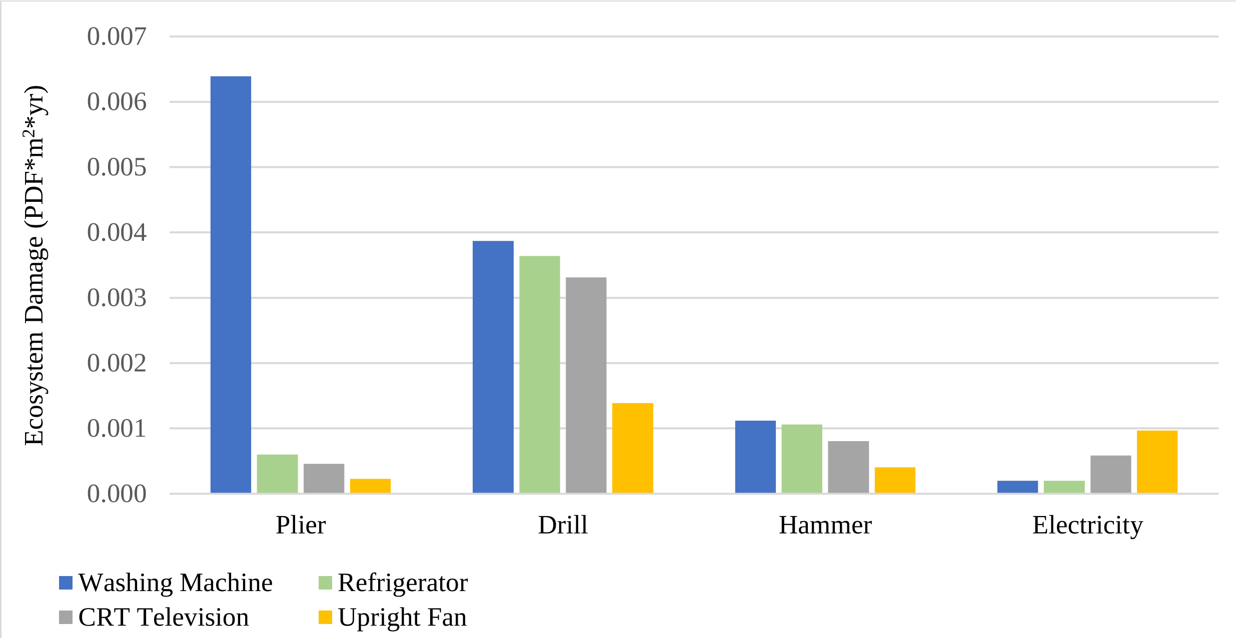


*Figure F-2 Ecosystem (PDF*m2*yr) endpoint damages in informal e-waste recycling by tool type per recycled product piece for four product types using Impact 2002+.*

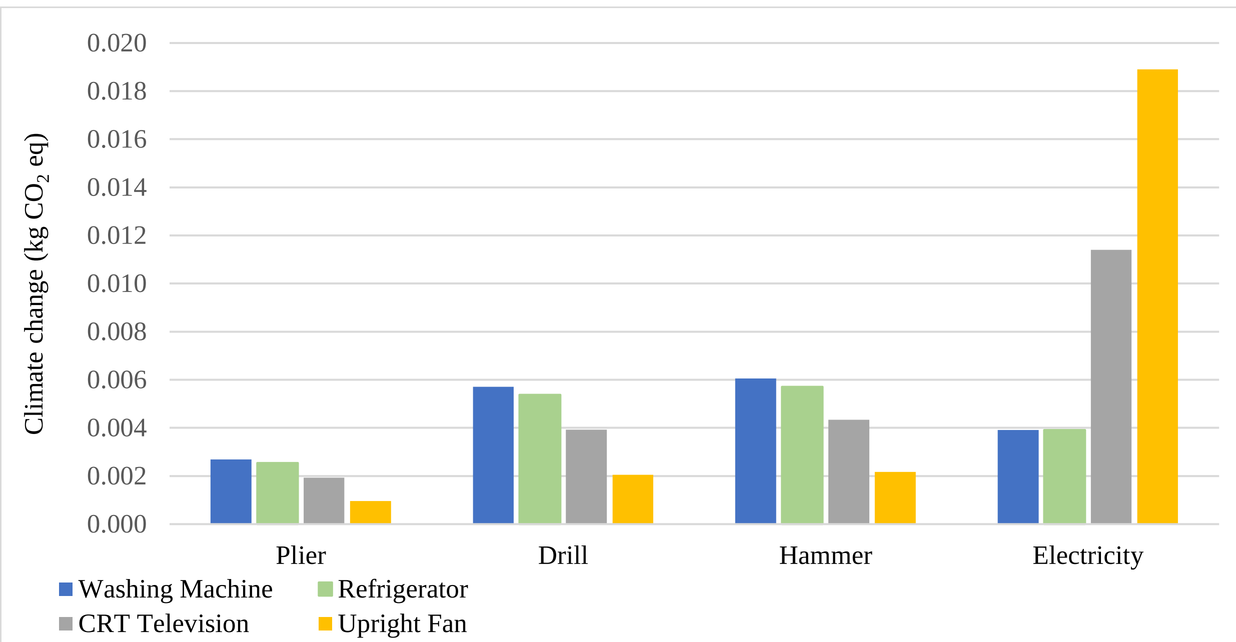


Figure F-3 Climate change (kg CO2 eq) endpoint damages in informal e-waste recycling by tool type per recycled product piece for four product types using Impact 2002+.

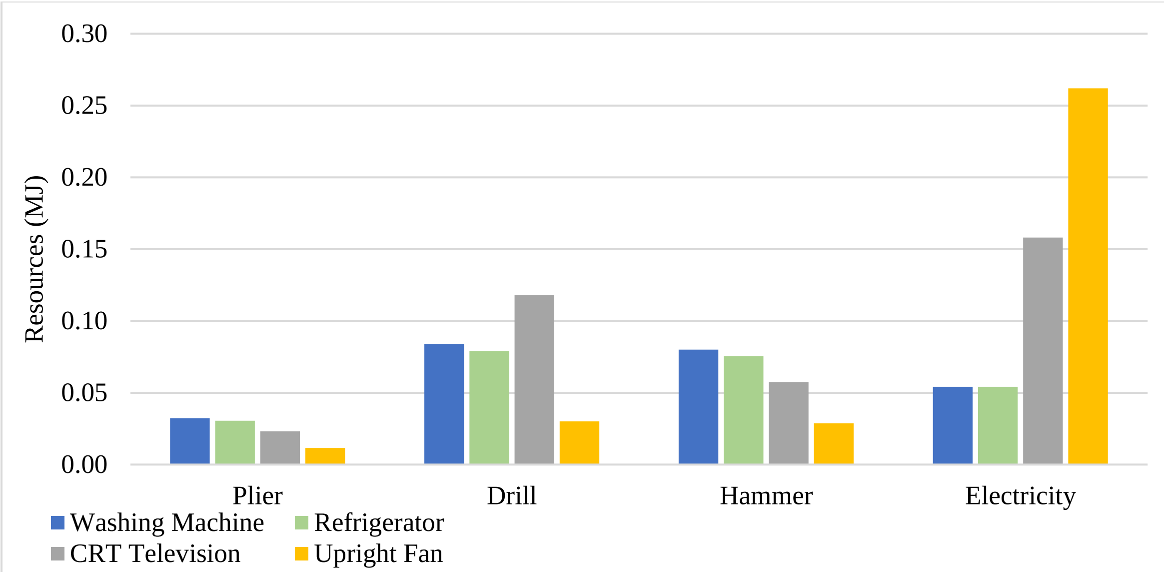


Figure F-4 Resources in MJ endpoint damages in informal e-waste recycling by tool type per recycled product piece for four product types using Impact 2002+.

F.2 Per product LCIA results

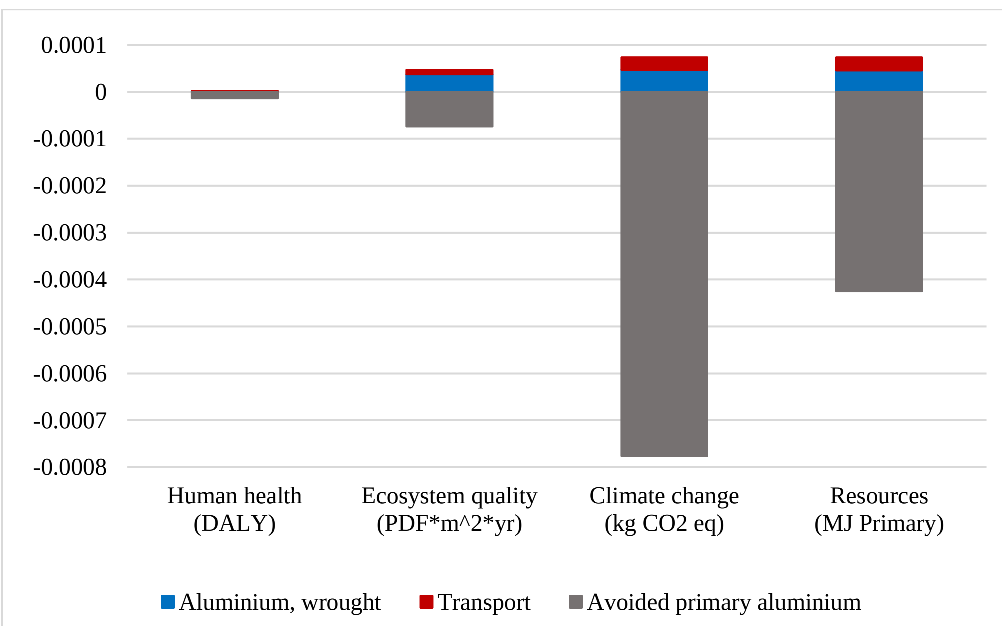


Figure F-5 Endpoint damages for human health, ecosystem quality, climate change, and resources for aluminum materials and processes.

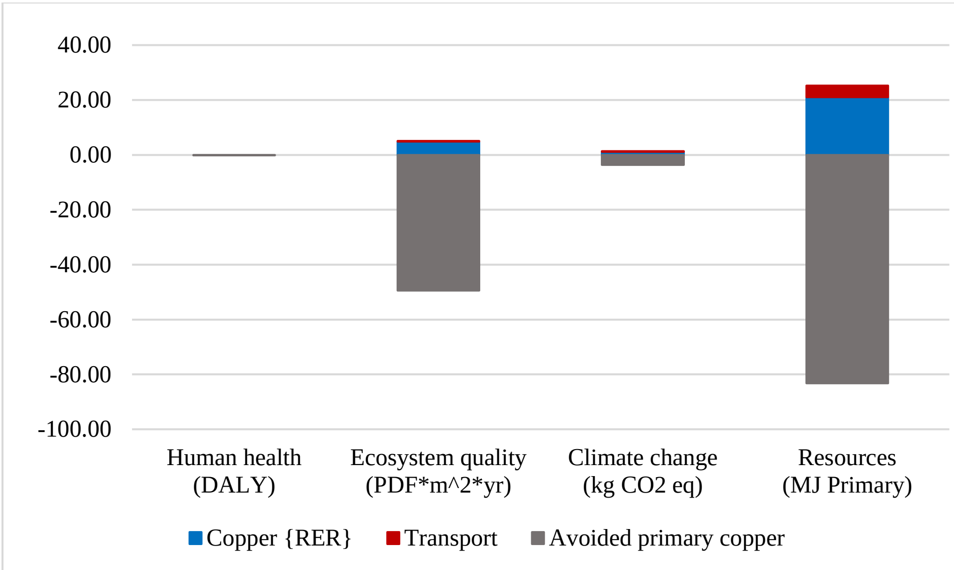


Figure F-6 Endpoint damages for human health, ecosystem quality, climate change, and resources for copper materials and processes.

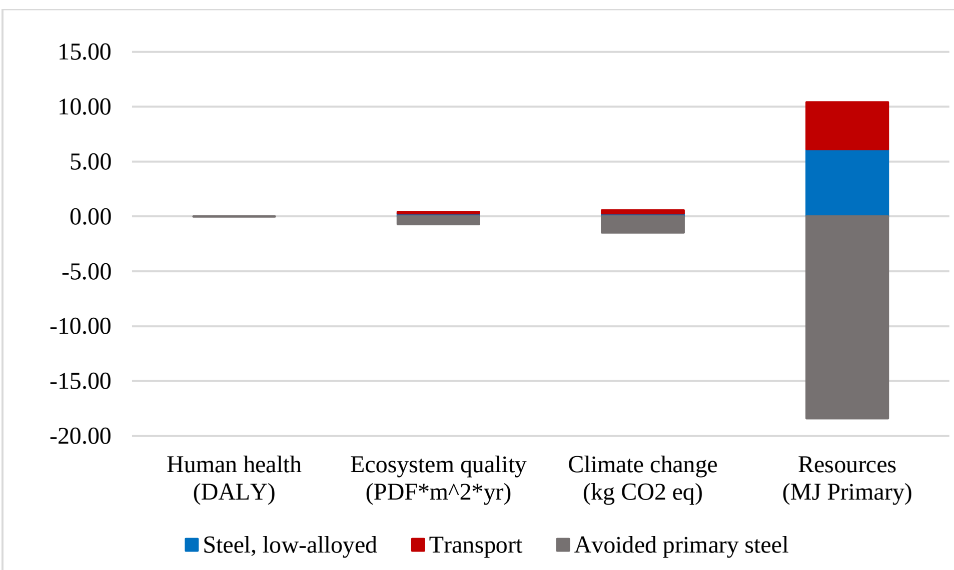


Figure F-7 Endpoint damages for human health, ecosystem quality, climate change, and resources for steel materials and processes.

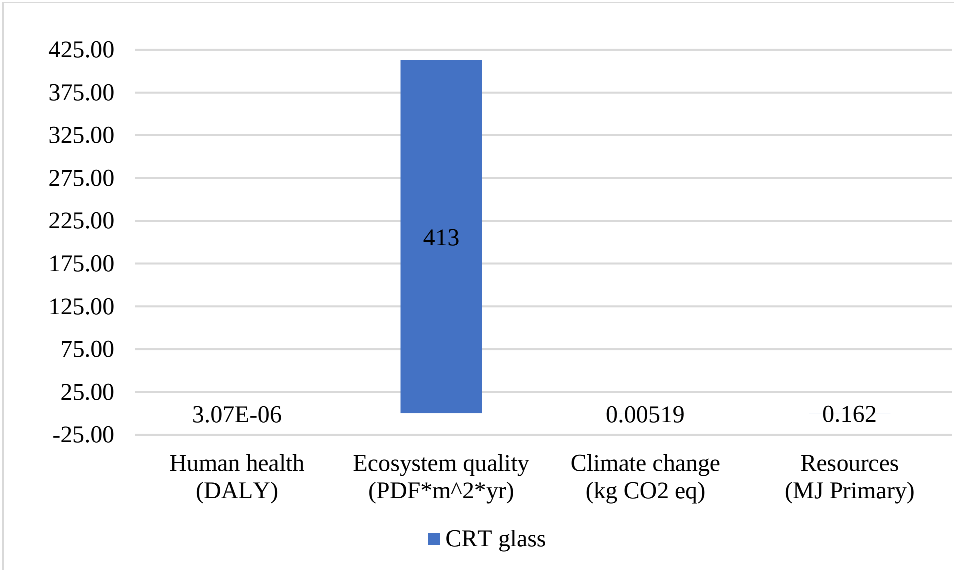


Figure F-8 Endpoint damages for human health, ecosystem quality, climate change, and resources for landfilling of CRT glass materials.

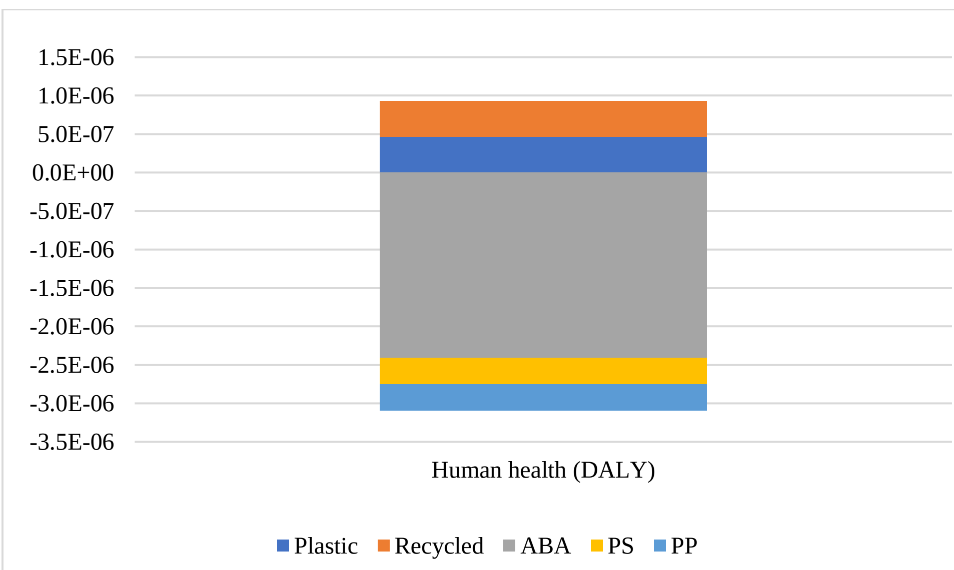


Figure F-9 Endpoint damages for human health for plastic recycling.

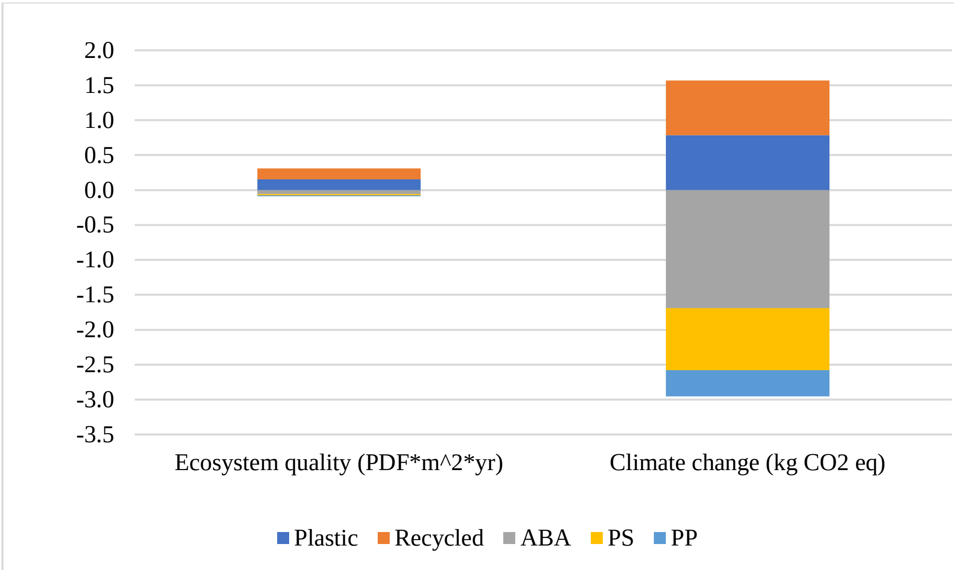


Figure F-10 Endpoint damages for ecosystem quality and climate change for plastic recycling.

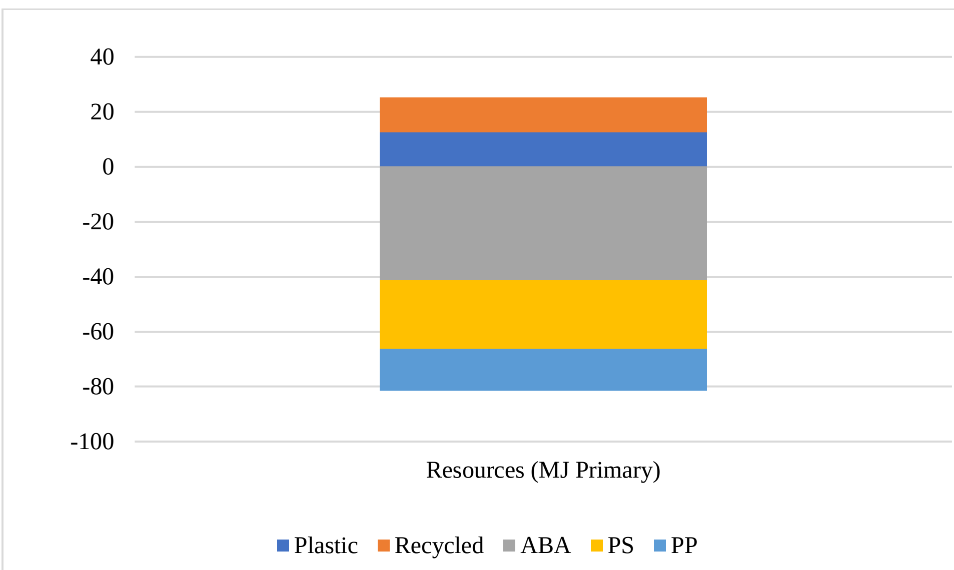


Figure F-11 Endpoint damages for resources for plastic recycling.

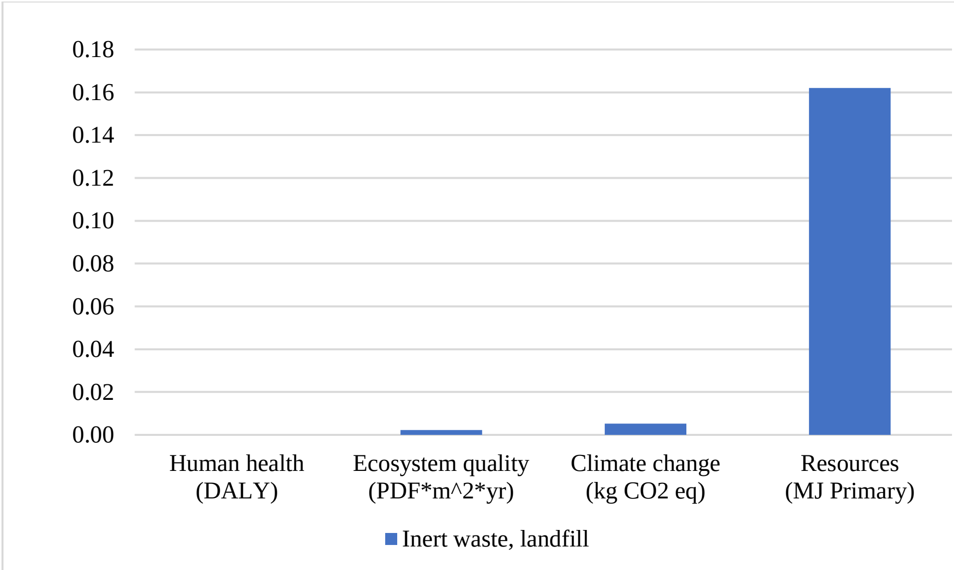


Figure F-12 Endpoint damages for human health, ecosystem quality, climate change, and resources for inert waste disposed of in landfill.

APPENDIX G:

LCA ReCiPe Results

G.1 ReCiPe LCIA midpoint damage category results by material type

Table G-7 Midpoint characterization by recovered material type using ReCiPe 2016 LCIA method.

Impact category*	**Avoided impact per kg material**							
Human health	**Aluminum**	**Copper**	**Steel**	**Cables**	**PCB**	**CRT glass**	**Plastic**	**Inert waste**
Human carcinogenic toxicity	-2.3	-4.3	0.5	-3.71	-18.5	5.3E-09	0.1	1.4E-04
Human non-carcinogenic toxicity	4.6	-701	-5.2	-657.0	-3,480.0	4.0E-07	0.8	1.7E-03
Fine particulate matter formation	-1.8E-02	-0.1	-2.83E-03	-0.1	-1.1	8.6E-09	3.6E-03	1.34E-05
Ozone formation, Human health	-9.9E-03	-3.0E-02	-7.4E-04	-3.4E-02	-0.2	4.1E-11	7.9E-03	4.5E-05
Ionizing radiation	-0.1	-3.0E-02	-5.2E-02	-0.2	-1.3	1.4E-12	1.3E-02	1.6E-04
Stratospheric ozone depletion	-2.2E-06	-8.0E-06	-2.2E-07	-8.2E-06	-4.3E-05	2.0E-12	3.5E-07	3.8E-09
Ecosystem quality								
Global warming	-6.9	-2.6	-1.0	-3.2	-20.5	1.5E-11	-2.7	5.4E-03
Ozone formation, terrestrial	-1.0E-02	-3.1E-02	-9.2E-04	-3.5E-02	-0.2	6.0E-12	-4.0E-03	4.6E-05
Terrestrial acidification	-3.7E-02	-0.3	-3.3E-03	-0.3	-3.6	6.5E-12	-6.8E-03	3.1E-05
Freshwater eutrophication	-1.9E-03	-0.1	-1.2E-03	-9.9E-02	-0.5	4.2E-13	2.3E-05	6.3E-07
Marine eutrophication	-2.3E-04	-1.5E-03	-3.0E-05	-1.5E-03	-7.6E-03	8.7E-17	-3.8E-05	5.1E-08
Terrestrial ecotoxicity	22.8	-3,800.0	-2.4	-3,360.0	-154.0	1.5E-13	1.4	1.3E-02
Freshwater ecotoxicity	-7.6E-02	-18.3	-0.2	-17.8	-101.0	1.3E-13	-4.0E-03	5.4E-05
Marine ecotoxicity	-9.3E-02	-27.1	-0.2	-26.2	-141.0	1.6E-14	-4.2E-03	8.4E-05
Land use	-3.7E-02	-0.2	-1.4E-02	-0.3	-2.0	8.4E-12	4.7E-03	9.5E-04
Water consumption	-0.2	-6.3E-02	-2.6E-03	-7.2E-02	-0.2	2.3E-12	-4.0E-02	1.7E-04
Resources								
Mineral resource scarcity	-0.2	-1.1	-8.3E-02	-0.8	-6.9	2.4E-06	7.9E-05	1.1E-05
Fossil resource scarcity	-1.1	-0.6	-0.2	-7.2E-02	-5.9	1.5E-03	-1.4	3.5E-03

*For units, see Table 4-2.

G.2 ReCiPe LCIA endpoint damage category results by material type

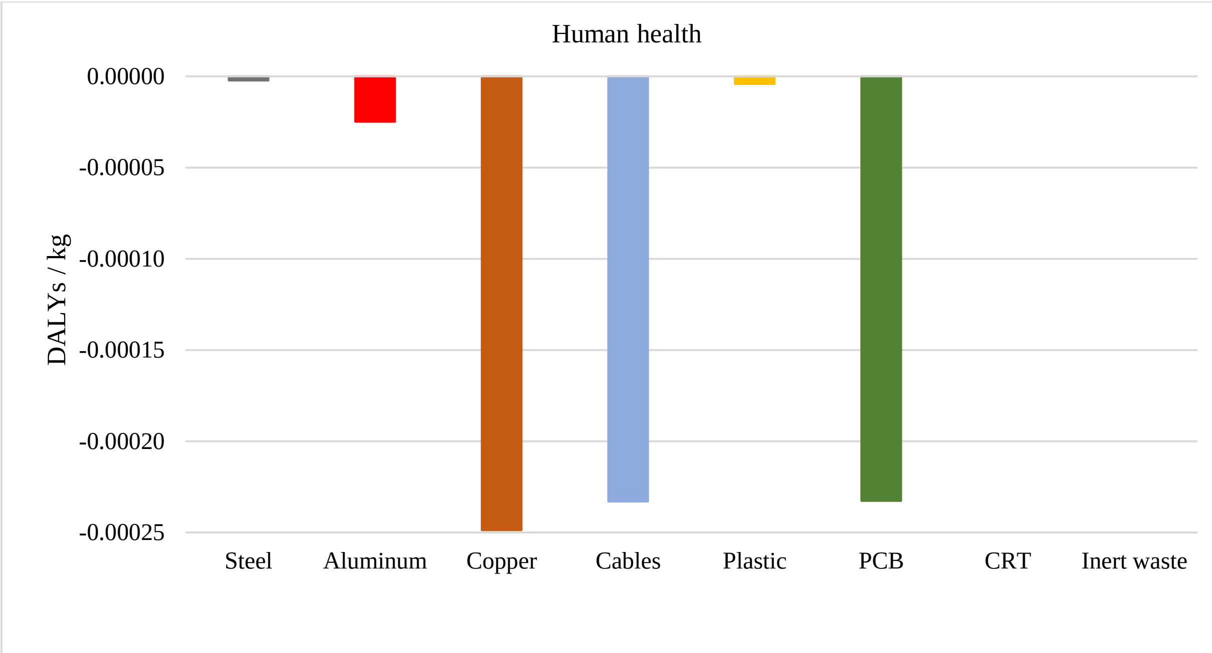


Figure G-1 Human health endpoint damages per kg material using ReCiPe 2016 LCIA method.

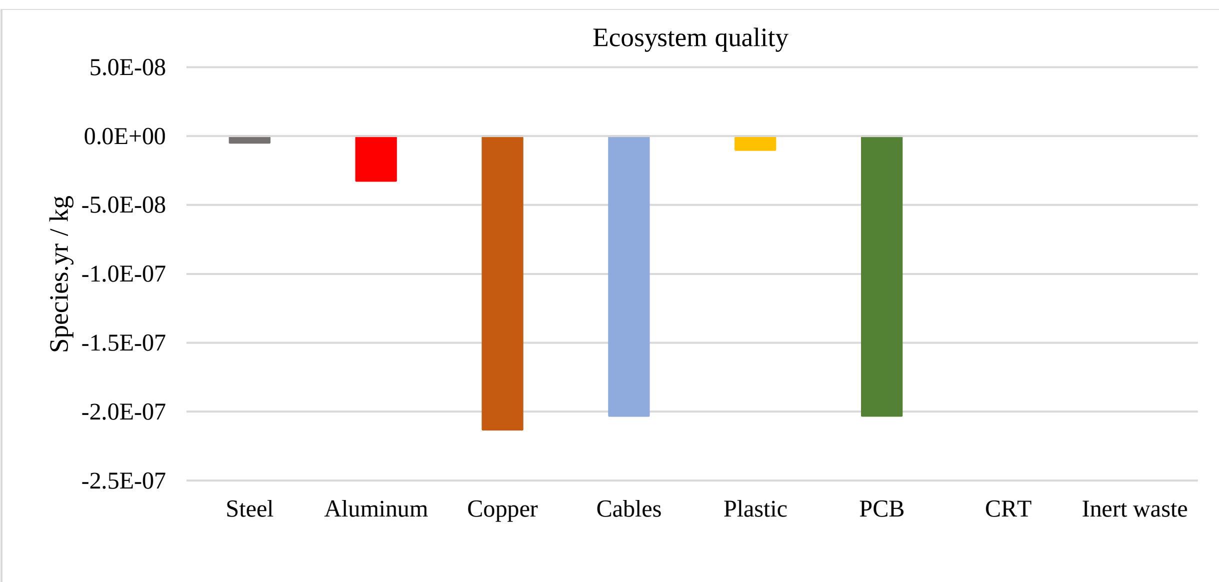


Figure G-2 Ecosystem quality endpoint damage assessment by material type using ReCiPe 2016 LCIA method.

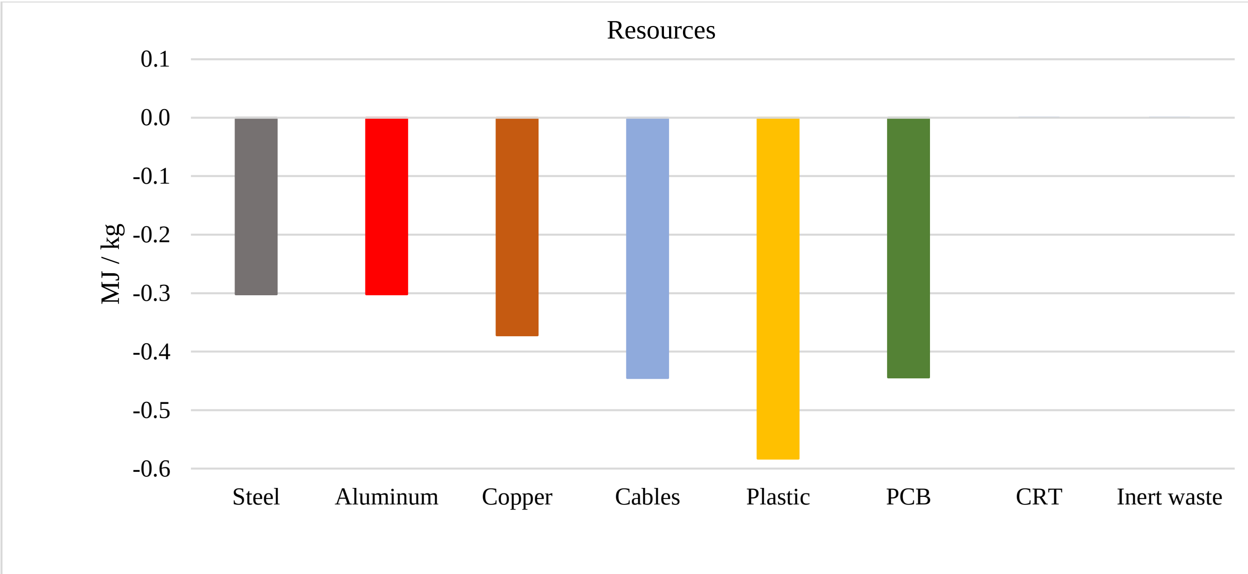


Figure G-3 Resources endpoint damage assessment by material type using ReCiPe 2016 LCIA method.

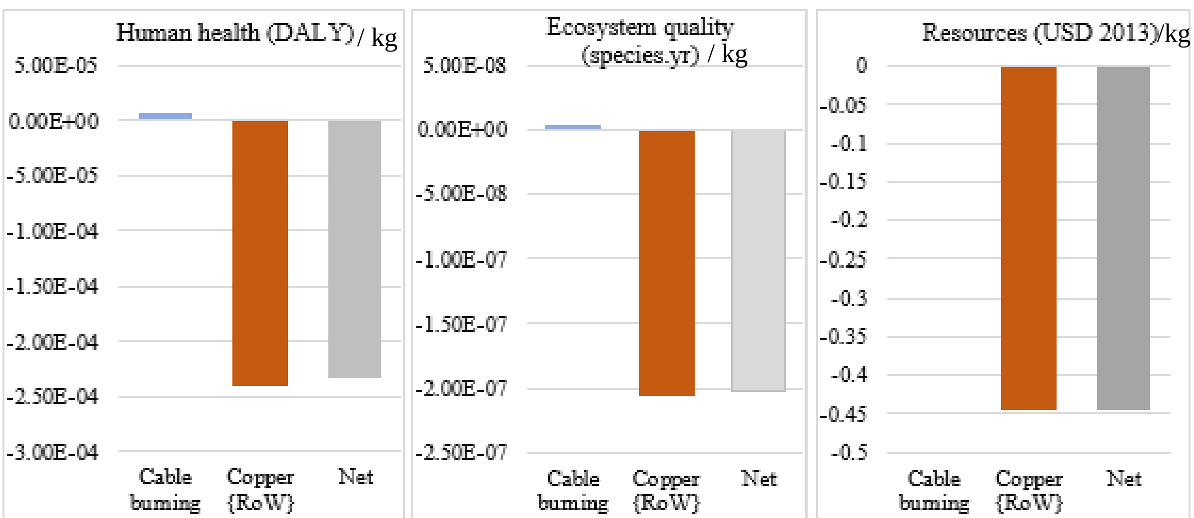


Figure G-4 Endpoint damage categories using ReCiPe LCIA method showing results for copper cable burning by process and material.

G.3 ReCiPe LCIA results by product

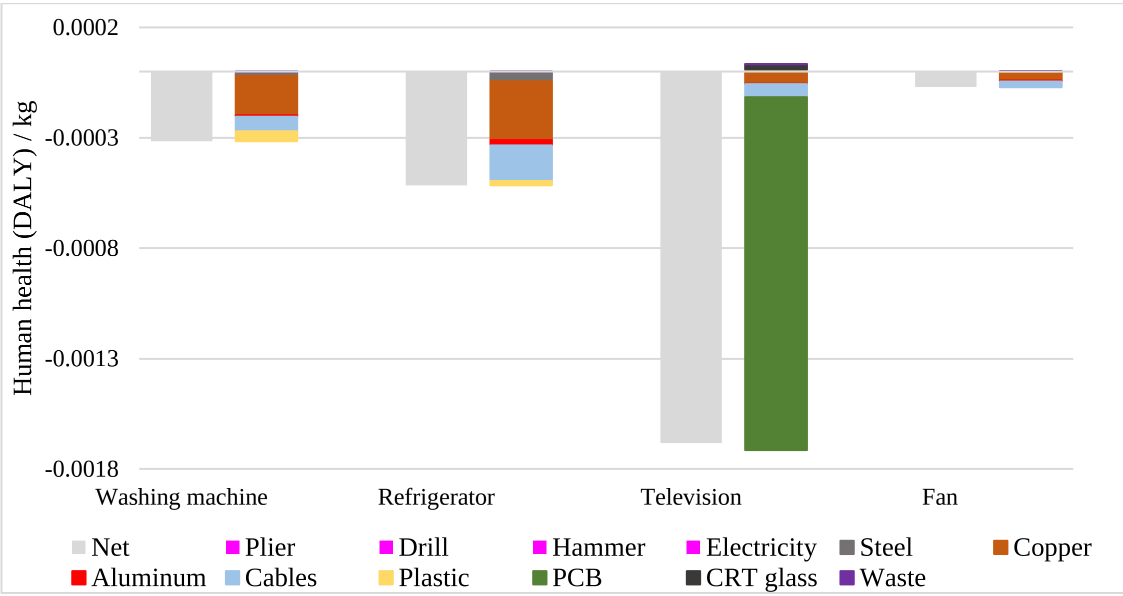


Figure G-5 Results of LCA using ReCiPe 2016 methods displaying human health damages (DALYs) by material recovered per e-waste product piece.

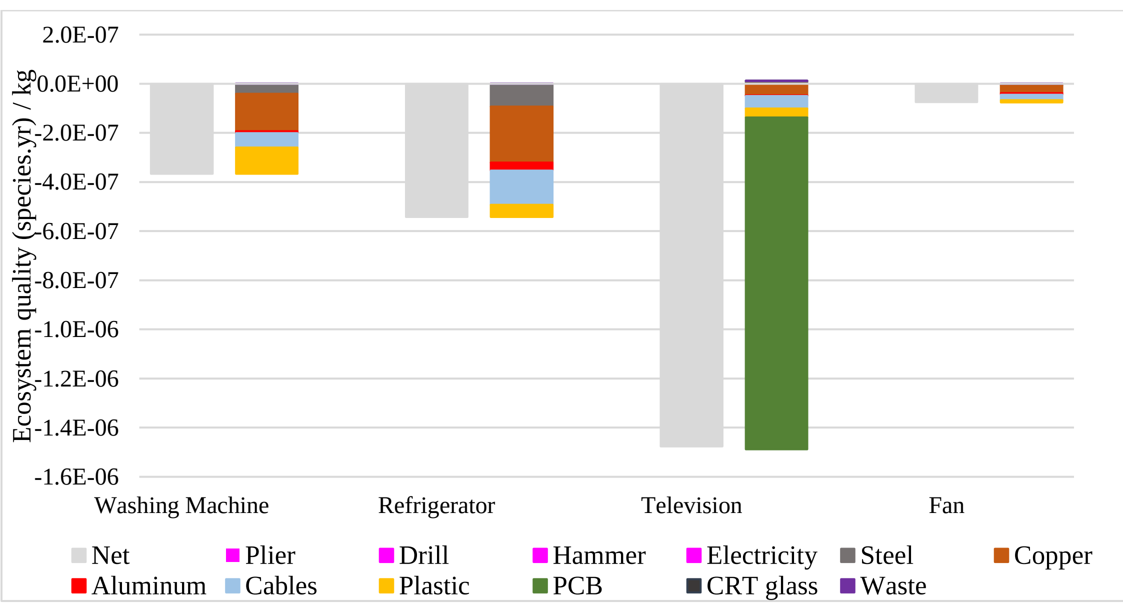


Figure G-6 Results of LCA using ReCiPe 2016 methods displaying ecosystem quality damages (Species.yr) by material recovered per e-waste product.

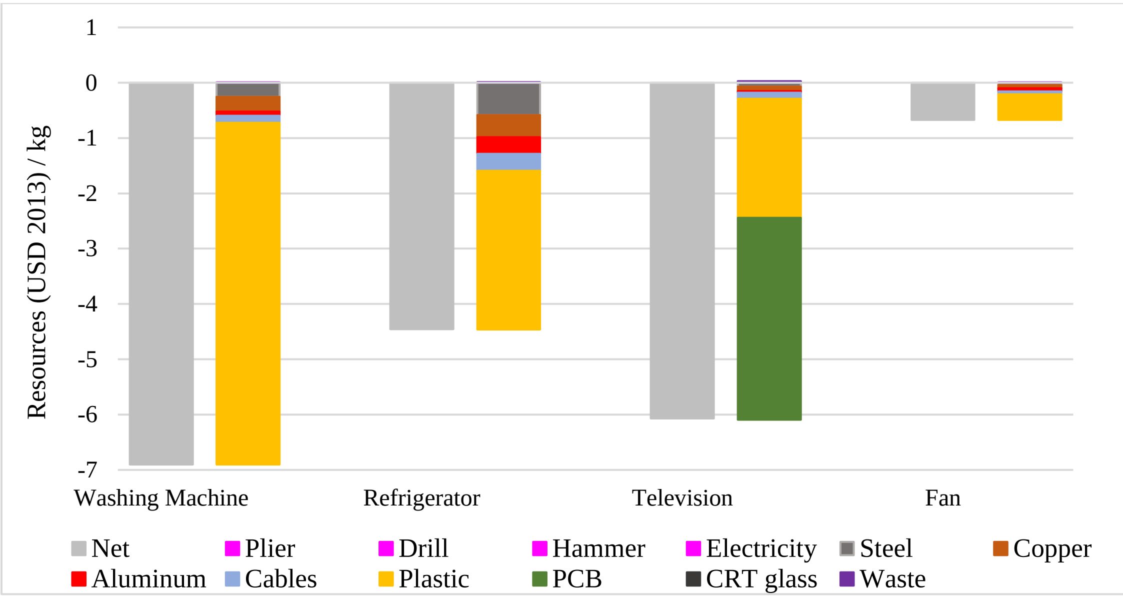


Figure G-7 Results of LCA using ReCiPe 2016 methods displaying resource damages (USD 2013) by material recovered per e-waste product.