Environmental and Health Impacts of Informal E-waste Recycling in Agbogbloshie, Accra, Ghana: Recommendations for Sustainable Management

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ABSTRACT

E-waste describes electrical and electronic equipment or parts of it that have been discarded by the owner without any intention of reuse. The annual global volumes of e-waste are rapidly increasing. In Ghana, the increasing quantities of e-waste have created avenue where the recovery of inherently valuable fractions from e-waste is performed by a dominating informal recycling sector using crude and primitive recycling procedures which pollute soil, water and the atmosphere with consequent threats to human health and the environment. This study examines the factors affecting current e-waste management in Ghana, the level and spatial extent of heavy metal pollution and contamination at the Agbogbloshie (AEPS) e-waste processing site in Accra, the ecological risks the metals pose, the carcinogenic and non-carcinogenic health risk of these heavy metals to children under six years, the possible loss of critical raw metals and the possibilities to mainstream the recycling activities of the informal sector. Methods used were experimental elemental analysis of nine heavy metals (Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb, Zn), field observations and interviews using structured questionnaires. The review of e-waste management and existing legislation in Ghana showed a lack of e-waste-specific legislation, inadequate infrastructure, lack of skills and human capacity, and low public awareness and education as factors affecting e-waste management in the country. The analysis of the selected heavy metals revealed that the concentrations at the AEPS exceeded the regulatory limits of both Dutch and Canadian Soil Quality and Guidance Values and that contamination extended beyond the main burning and dismantling sites of the informal recyclers to the school, residential, recreational, clinic, farm and worship areas. For five out of nine heavy metals, geostatistical analysis reveals normal distribution, spatial variability and spatial autocorrelation using the Moran index at a Z-score greater that 1.6 at p-value less than 0.05. The health risk assessment using the hazard index for both carcinogenic and non-carcinogenic elements indicates that Cr and Pb with a hazard index above the 1 threshold of unacceptable limit pose significant health risks (neurological and developmental disorders) to children under six years. It can be concluded that an appropriate mix of legislation, infrastructure, and local and international collaboration, together with the ability to enforce and ensure the mainstreaming and integration of the informal recyclers could help minimize the environmental and health risks and loss of critical rare earth metals from e-waste processing in Ghana.

Umwelt- und Gesundheitsschäden durch die Aufbereitung von Elektroschrott im informellen Sektor in Agbogbloshie, Accra, Ghana: Empfehlungen zum Nachhaltigkeitsmanagement

KURZFASSUNG

Elektroschrott besteht aus elektrischen und elektronischen Geräte oder Bauteilen, die ausrangiert wurden und nicht mehr eingesetzt werden können oder sollen. Das Aufkommen von Elektroschrott wächst global rapide an. Elektroschrott besteht sowohl aus lokal erzeugtem Abfall, wie aus elektrischen und elektronischen Geräte und Elektroschrott, der unter Vorwand als gebrauchte Geräte oder Spenden aus Industrieländern in Entwicklungsländer wie Ghana exportiert wird. Die Rückgewinnung von Wertstoffen aus dem Schrott erfolgt dort vorrangig durch den informellen Sektor unter Anwendung von groben und primitiven Recyclingverfahren, die Boden, Wasser und Atmosphäre verschmutzen und dadurch die Gesundheit der Menschen und die Umwelt bedrohen. Diese Arbeit untersucht das Wirkungsgefüge der Elektroschrottverwertung in Ghana, insbesondere Umfang und räumliche Verteilung von Schwermetallbelastung und -kontamination in der Agbogbloshie e-Waste Processing Site (AEPS) in Accra, die von den Schwermetallen ausgehenden ökologischen Risiken, die krebserregenden und nichtkrebserregenden Gesundheitsrisiken für Kinder unter 6 Jahren, den möglichen Verlust von seltenen Metallen und die Möglichkeiten zur Regulierung der Recyclingaktivitäten des informellen Sektors. Zur Datenerhebung wurden Methoden der Laboranalyse von 9 Schwermetallen (Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb, Zn), Begehungen des Untersuchungsraumes und Befragungen mit standardisierten Fragebögen eingesetzt. Die Untersuchungen zur Elektroschrottverwertung und der bestehenden Gesetzgebung in Ghana deckten Gesetzeslücken, Infrastrukturmängel, Defizite in Fachkunde und Qualifikation und vor allem geringe öffentliche Problemwahrnehmung und Sensibilisierung auf. Die Analyse der ausgewählten Schwermetalle zeigten, dass die Verunreinigungen in der AEPS die Grenzwerte sowohl der kanadischen wie der niederländischen Bodenschutzvorschriften überschreiten und das die Kontaminationen über die Verarbeitungflächen des informellen Sektors hinweg auch Wohngebiete, schulische und kirchliche Einrichtungen, Freizeiteinrichtungen und landwirtschaftliche Flächen beinträchtigen. Für 4 der 9 Schwermetalle wurden geostatistische Analysen durchgeführt und Normalverteilung, räumliche Variabilität und räumliche Autokorrelation ermittelt. Der Moran Index erreicht einen Z-Wert von größer 1,6 und einen p-Wert kleiner 0,05. Zur Bewertung der Gesundheitsrisiken wurde der Risikoindex für karziogene und nichtkarziogene Stoffe ermittelt. Der Risikoindex liegt bei Cr und Pb mit 1 über dem Grenzwert für zulässige Konzentrationen und belegt ein signifikanten Gesundheitsrisiko (für neurologische Schäden und Entwicklungsstörungen) für Kinder unter 6 Jahre. Auf der Agbogbloshie e-Waste Processing Site wurden daneben auch Ablagerungen von Seltenen Erden festgestellt, für die eine kaum zu deckende Nachfrage herrscht.

Abschließend kann festgestellt werden, dass eine geeignete Kombination aus Gesetzgebung, Infrastrukturverbesserung und lokaler und internationaler Zusammenarbeit in Verbindung mit Maßnahmen zur Regulation und Integration des informellen Recyklingsektors die Umwelt- und Gesundheitsrisiken und den Verlust Seltener Erden bei der Elektroschrottaufbereitung in Ghana auf ein Mindestmaß reduzieren kann.

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1 INTRODUCTION

1.1 Problem statement

Changing lifestyles of the consumers of electrical and electronic equipment (EEE) and growing demand for newer and more efficient technologies have seen the production of EEE as one of the fastest growing sectors in the manufacturing industry (Gupta 2011; El-Nakib 2012; Maxwell 2013). The situation has resulted in the short life span of EEE, thus making it become obsolete or discarded at a rapidly increasing rate around the world. The StEP Initiative (2014) described electrical and electronic equipment or its parts that have been discarded by their owners with no intention of reuse as electronic waste (e-waste). The StEP Initiative (2015) estimates that 41.8 million tons of e-waste (mostly microwaves, toasters, video cameras, washing machines, cloth dryers and electric stoves) found their way into dump yards with the USA and China discarding nearly 33% of the world's total e-waste. These obsolete and discarded EEE are legally or illegally exported from developed to developing countries (Figure 1.1) under the disguise of slightly used or charity EEE, although an unconfirmed amount arrives as e-waste which cannot be reused. The UNEP (2005) estimated that 50-80% of EEE collected for recycling in developed countries ends up in dumping and recycling centers of developing countries with China and India receiving the largest amount.

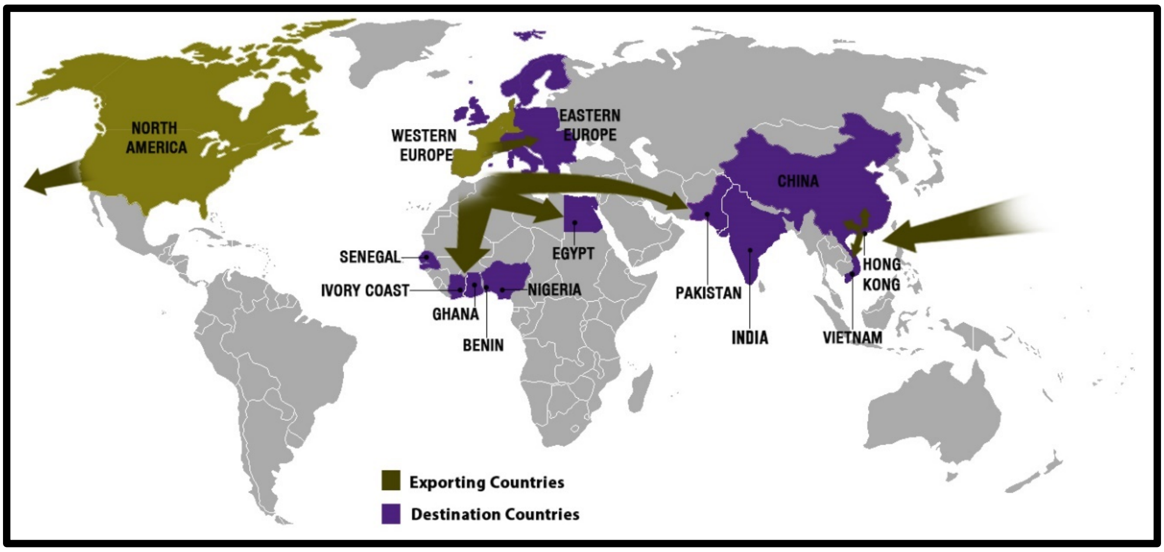

Figure 1.1: Global flow of legal and illegal e-waste trade (Source: Greenpeace, Basel Action Network)

In recent times, Ghana has become one of the main dumping grounds for e-waste in the world with its Agbogbloshie E-waste Processing Site (AEPS), located close to the central business district of the capital city Accra and nicknamed the “graveyard” for e-waste. The largely dominating unregulated informal sector collects and recycles 97% of the e-waste in Ghana using unconventional, primitive and crude procedures (Figure 1.2) to recover valuable metals. However, these activities pose huge health and environmental risks to humans, aquatic and terrestrial species. These risks are due to the release of toxic or hazardous substances such as heavy metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and brominated flame retardants (*BFRs*) into the environment. In addition, the inefficient procedures contribute to the loss of rare earth metals inherent in e-waste. This was confirmed by Schluep et al. (2013), who revealed that the informal recovery of valuable metals yields only 25% efficiency, which is in sharp contrast to current formalized recycling systems that use state-of-the-art integrated smelters, and are able to achieve efficiencies as high as 95% (Chancerel et al. 2009; Schluep et al. 2013).

Increased quantities of e-waste in Ghana have created an avenue for individuals to make a living by utilizing unconventional, uncontrolled, primitive and crude procedures to recycle and recover valuable metals from this waste. Further, the absence of a well-structured management strategy has resulted in the informal recycling sector polluting the environment and having negative health impacts on humans, aquatic and terrestrial organisms. The problem that needs to be solved involves the determination of both the quantitative and qualitative characterization of the pollutants, pathways, ecological risks, health risks and loss of rare earth metals. With growing environmental and public health concerns on the current recycling and management of e-waste in Ghana, there have been calls for formal recyclers to enter into the e-waste management system as they could manage the sector in a more environmentally sustainable manner using Best Available Technology.

Although, several studies have all looked at various aspects of the e-waste situation in Ghana by (Brigden et al. 2008; Oteng-Ababio (2010); Caravanos et al. (2011); Atiemo et al. (2012); Grant and Oteng-Ababio (2012); Asante et al. (2012), there are still questions such as what are the factors affecting management, what are the environmental and health impacts of current recycling activities in Ghana, which rare earth metal are lost and what is the level or concentration, could there be neurological, developmental and carcinogenic health risk for people within and beyond recycling sites, will the entry of formal recyclers come at the expense of the informal recyclers, and what are the options to mainstream the activities of both informal and formal recyclers? This research therefore seeks answers to these question as the answers will help in achieving the overall objective, which is to examine sustainable e-waste management options for the e-waste challenges in Ghana.

Figure 1.2: Typical scenes at e-waste recycling sites in Ghana (Source: Pwamang (2009))

1.2 Research objectives

The main objective of this research aims at examining sustainable e-waste management options and the impacts of e-waste activities in Ghana.

1.2.1 Specific objectives

The specific objectives of the study are to:

i. Assess the factors affecting the efficient management and governance of e-waste in Ghana.

ii. Examine the impacts to the environment, human health and loss of rare earth metals from e-waste recycling activities in Ghana.

a) Quantify heavy metal contaminants in soils from the Agbogbloshie e-waste processing site.

b) Examine the spatial extent of heavy metal contamination and the potential ecological risk heavy metals pose to the environment.

c) Determine the health risk and hazards posed by heavy metals to human health.

d) Identify the critical raw metals lost in the current recycling process.

iii. Identify the options to mainstream the informal sectors of e-waste management in Ghana.

1.3 Research questions

The study investigates and searches for answers to the following questions:

i. What are the factors affecting the efficient management and governance of e-waste in Ghana?

ii. What are the impacts to the environment, health risks and loss of rare earth metals of the activities of informal e-waste recyclers in Ghana?

a) What is the level or concentration of heavy metals within the AEPS?

b) To what extent does heavy metal contamination spread within the AEPS?

c) How does heavy metal contamination pose health risks to humans?

d) Which critical metals are lost due to the informal recycling activities within the AEPS?

iii. Can the informal e-waste recycling be mainstreamed and what could be the options for mainstreaming the informal sectors in e-waste management in Ghana?

1.4 Conceptual framework of the study

The conceptual framework of this study translates the mechanics of the essential factors that are influencing the sectors in e-waste recycling and attempts to establish the causal relationships among them (Figure 1.3).

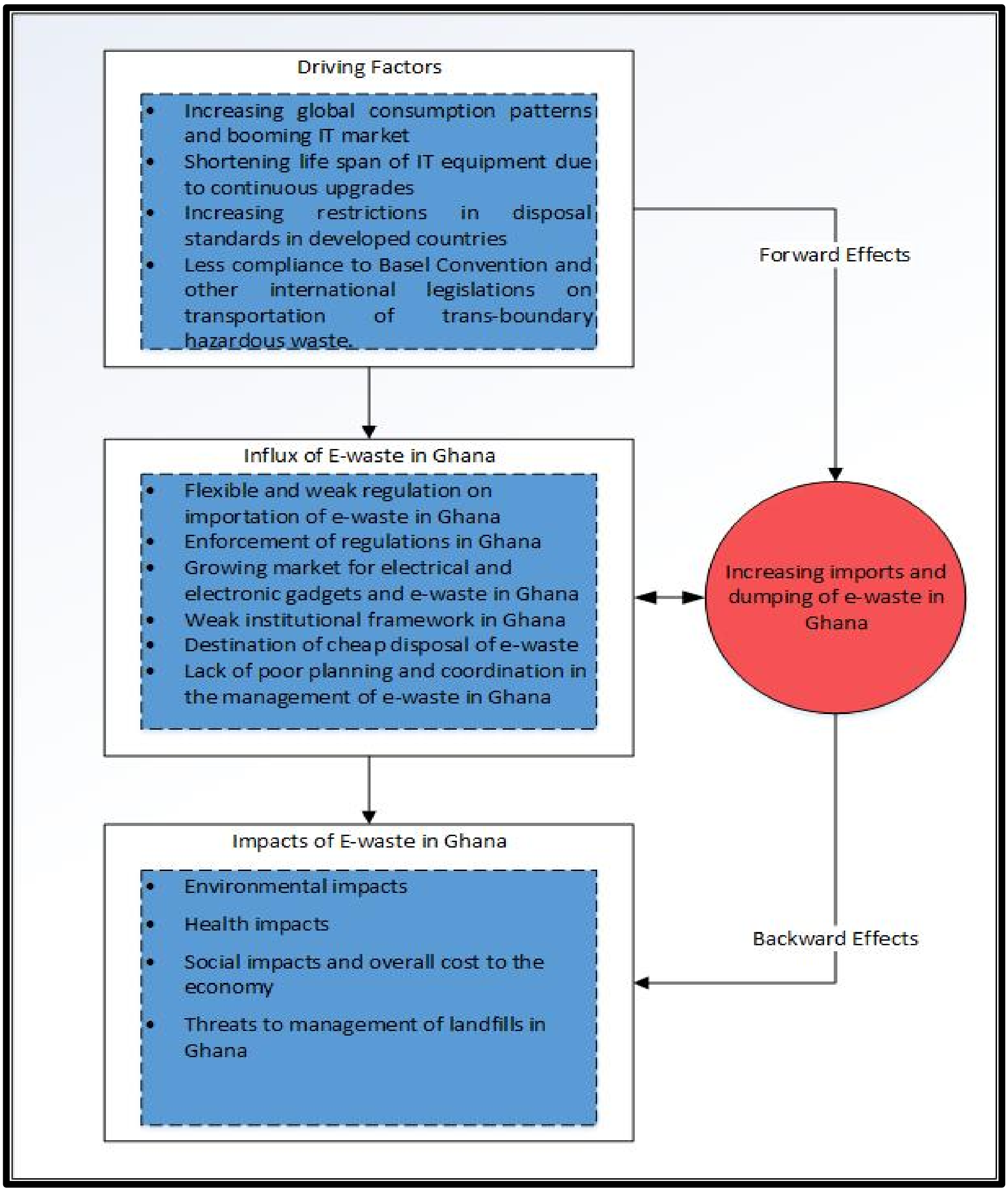

Figure 1.3: Conceptual Framework

1.5 Overall research approach

The study consists of four phases (Figure 1.3).

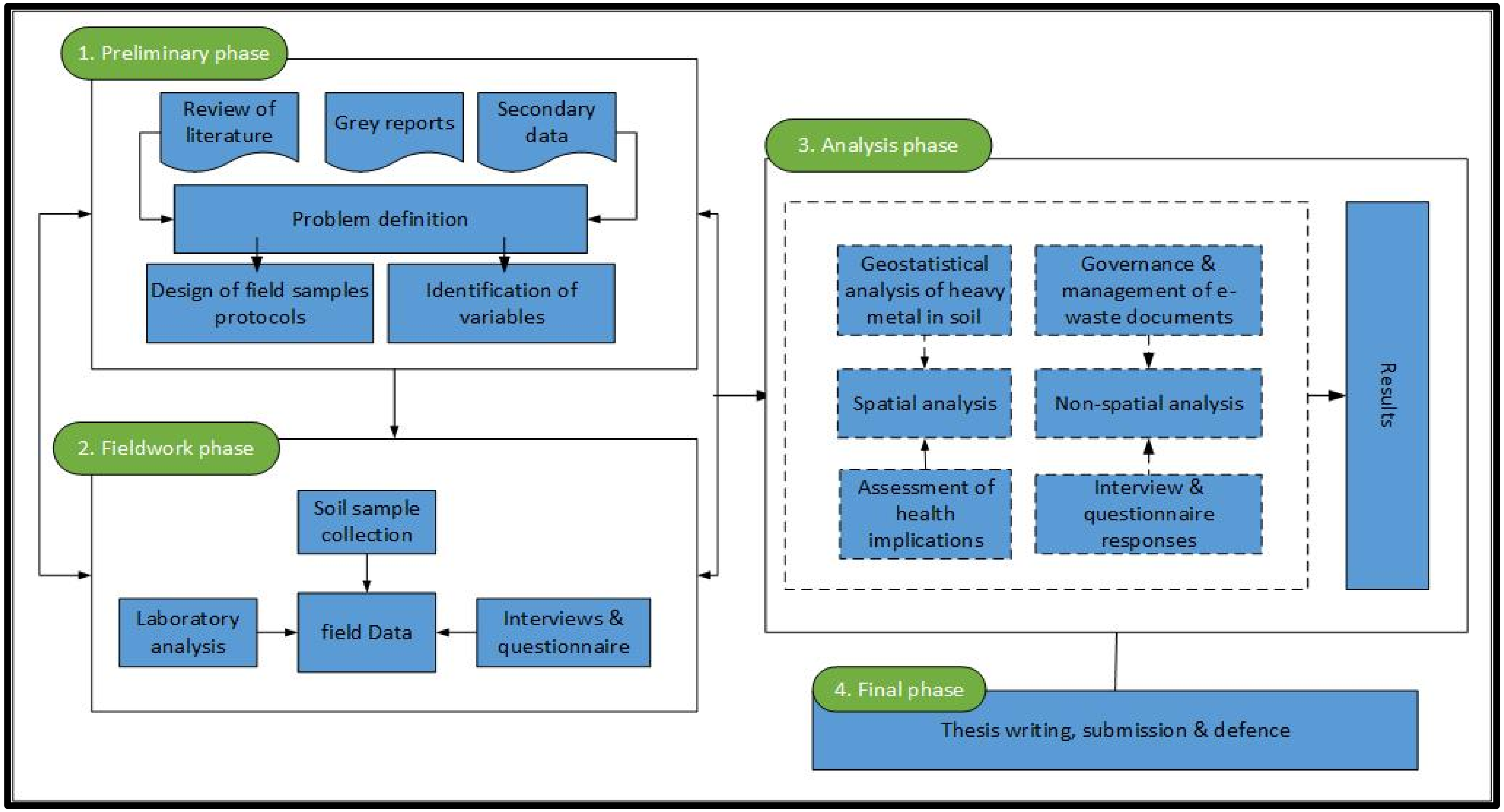

Figure 1.4: Research approach

1.5.1 Preliminary phase

In this first phase of the research, literature review was conducted, secondary data collected, and the activities of stakeholders involved in the e-waste chain observed. Extensive reviews of research, policy and legislative documents were also conducted. From these activities, the design of field samples and variables to be measured was done.

1.5.2 Fieldwork phase

In the fieldwork phase, measurements of variables in the study were conducted. Collection of soil samples from the AEPS was done, and stakeholders and other key informants in the e-waste chain interviewed. Laboratory analyses were performed to identify heavy the metals and rare earth metals in the soil samples collected from the study area.

1.5.3 Analysis phase

Both spatial and non-spatial analyses were done on the measured variables. Responses from interviews analyzed and environmental and human health risk assessments were done.

1.5.4 Final phase

The final phase comprised general assessment of e-waste and quantification of the impacts on which basis implications for future policies were drawn.

1.6 Projected research outcomes

The expected outcomes of this research are outlined as follows:

i. Documentation of the factors affecting efficient management of e-waste in Ghana.
ii. Impacts on the environment and human health, and loss of rare earth metals through e-waste recycling activities in the AEPS.

a) Levels of heavy metal contamination
b) Spatial extent of heavy metal contamination and potential ecological risk

c) Hazard index for carcinogenic and non-carcinogenic health risks for children under six years
d) Rare earth metal loss due to unconventional processing methods

iii. Proposed framework to bridge the gap between the formal and informal sectors in the e-waste management sector.

1.7 Thesis structure

Chapter 1 introduces the research conducted, defines the problem of e-waste in Ghana, states the research objectives and questions in the study, and gives a flow diagram on the conceptual framework and research approach adopted. The expected outcome of the research is also outlined in this chapter.

Chapter 2 presents with the summary of reviewed literature on effects of e-waste activities on environment, health, landfills as well as the social and economic impacts of e-waste transactions. Literature was also reviewed on the influx of e-waste in Ghana and factors that drive these activities and e-waste legislation. Methodological issues to be employed in investigating this study were also reviewed.

In Chapter 3, information on the study area with regard to location and size, climate, geology, vegetation, occupations of the inhabitants, population and history of e-waste activity within the study area is addressed. The methods, software and materials used for the research are also provided.

The results of the research are presented and discussed in Chapter 4 together with the assessment of factors affecting the efficient management and governance of e-waste in Ghana and determination of the impacts of informal recyclers' activities on environment, health and critical raw resources. Chapter 6 provides conclusions and recommendations.

2 LITERATURE REVIEW

2.1 Overview, quantities and flow of e-waste

This section looks at the definition of e-waste, material composition, effects of the chemical composition on the environment and health. Quantification, flow and routes of waste into destination countries will also be examined.

2.1.1 Definition and material composition of e-waste

The definitions of e-waste or waste electrical electronic equipment (WEEE) vary depending on the needs of the owner, exporter, importer and country of origin or country of last use or possession. The StEP Initiative (2014) defined e-waste as all types of electrical and electronic equipment (EEE) and its parts that have been discarded by the owner as waste without the intention of re-use. Puckett and Smith (2002) defined e-waste as consisting of electronic devices ranging from household appliances such as refrigerators, air conditioners, cell phones, personal stereos, and consumer electronics that have been discarded by their users. The EU waste electrical and electronic equipment WEEE Directive (2002) defined e-waste as including all components, sub-assemblies and consumables that are part of the electrical or electronic product at the time of discarding, while the US EPA referred to e-waste as waste or discarded electrical and electronic products such as computers, televisions, video games, consoles, monitors and electrical devices that operate using a program or printed wiring boards (PWB). Widmer et al. (2005) also defined e-waste as electrical or electronic devices that have ceased to be of value to their owners. Ghana in its Hazardous and E-waste Management Bill of 2011 adopted the definition of e-waste as discarded electronic equipment inclusive of all components, sub-assemblies and consumables which are part of the product at the time of discarding.

There are 10 e-waste categories including, large and small household appliances, IT, and lighting equipment. Though there is a lack of one standard definition for this stream of waste indicating the complexity of this stream of waste, the characterization of e-waste is seen as a very important step to understand the physical properties of e-waste in order to develop cost-effective and environmentally sound management of e-waste. Cui and Forssberg (2003) even proposes that a further in-depth characterization of e-waste is imperative if effective separation of resource metals for recycling is to be achieved. E-waste is known to consist of both valuable and hazardous fractions where, for example, a printed circuit board contains up to 40% metal, 30% plastic and 30% ceramics (Cui and Forssberg 2003). In general, the material composition of e-waste is around 60% metals, 15% plastic, 12% screen (LCDs and CRTs), 5% metal-plastic mixture, 3% pollutants, 2% cables, 2% printed circuit boards, and other fractions accounting for 1% (Cui and Forssberg 2003; Widmer *et al*. 2005).

Although the pollutant or hazardous fraction makes up only around 3% compared to the entire material composition, improper handling and disposal pose a significant threat to human health (overdoses of the trace metals or pollutants are said to cause cancer) and the environment (Table 2.1).

Table 2.1: Hazardous fractions of EEE and its effect on environment and health

Hazardous Fraction	**Component of EEE**	**Health and Environment Effects**
Lead (Pb)	Printed circuit boards, cathode ray tubes, light bulbs, monitors, batteries	-Affects the kidneys and can damage nervous system of children. -Causes blood and brain disorders.
Mercury (Hg)	Monitors, printed circuit boards, cells, fluorescent lamps	-Bio-accumulates causing brain and liver damage if ingested or inhaled.
Chromium (Cr)	Anticorrosion coatings, data tapes, floppy disks	-Can cause irritation to the eyes, skin and mucous membranes. -Can cause permanent eye injury damage to DNA.
Cadmium (Cd)	Switches, batteries, infrared detectors, chips, copiers, cathode ray tubes, phones	-Exposures cause flu-like symptoms of weakness, fever and muscular pain while; long-term exposure causes lung cancer and kidney damage.
Barium (Ba)	Cathode ray tubes, fluorescent lamps	-Short-term Ba exposure could lead to brain swelling, muscle weakness, damage to the heart, liver and spleen.
Nickel (Ni)	Power supply boxes, computers, x-ray equipment, ceramic components of electronics	-Exposure can cause lung cancer and a form of skin disease that is characterised by poor wound healing and wart-like bumps.
Zinc (Zn)	Batteries, cathode ray tubes, soldering flux, and wood preservatives	-Can cause stomach cramps, skin irritations, vomiting, nausea and anaemia. High levels of zinc can damage the pancreas. Extensive exposure to zinc chloride can cause respiratory disorders.
Copper (Cu)	microprocessors, transformer coils, cables terminal strips, plugs and sockets	Exposure to copper can cause irritation of the nose, mouth and eyes and it causes headaches, stomachaches, dizziness, vomiting and diarrhea. High uptakes of copper may cause liver and kidney damage and even death

In order to reduce these substances and other hazardous fractions in the e-waste, the European Union in 2003 adopted the Restriction of Hazardous Substances Directive 2002/95/EC, (RoHS). Nevertheless, banned substances such as polychlorinated biphenyl have been measured in some e-waste disposal sites in Ghana. It might however be too early to assess the impact of this legislation in reducing hazardous chemicals in EEE.

2.1.2 Quantification and routes of e-waste

Müller et al. (2009) indicated difficulties in estimating the quantities of e-waste. However, improvements in both data sources and methods of estimations such as:

- The ‘consumption and use method’, which takes the average equipment of a typical household with electrical and electronic appliances as the basis for a prediction of the potential amount of e-waste.
- The ‘market supply method’, which uses data on production and sales in a given geographical region
- The Swiss Environmental Agency's estimates based on the assumption that private households are already saturated and for each new appliance bought, an old one reaches its end-of-life.
- The Carnegie Mellon University method of estimation only applicable in the USA is based on sales data (Matthews *et al*. 1997).

The above methods have improved the estimation accuracies of e-waste volumes around the globe. According to the Step Initiative (2013) 45 million tons of e-waste were generated globally in 2012, and are expected to jump to 65 million tons by 2017, i.e. an increase of about 33%. E-waste is mainly generated in industrialized or developed countries, with the USA, China and Europe leading the amount of e-waste generated with 9.7, 7.9 and 6.5 million tons respectively and shipped to developing countries not only as charity or donations to developing countries but also as trade (Figure 1.1). Changing lifestyles and constant upgrading of electrical and electronic equipment are seen as factors contributing to the increasing amounts of obsolete equipment and the subsequent discarding as e-waste. Additionally, due to stricter regulations and the high cost of recycling and disposal of e-waste in developed countries, discarded EEE in these countries are packaged and shipped to less developing countries, including Ghana as secondhand, slightly used or charity EEE (Ongondo et al. 2011). Although the Basel convention on trans-boundary movement of hazardous waste restricts trans-boundary trade of e-waste (because they exhibit hazardous characteristics), there are reports by INTERPOL, though with no confirmed figures, which indicate both legal and illegal traffic of e-waste from developed to less developed countries (INTERPOL 2009). The reports further indicated that the amount of e-waste shipped from developed nations to developing countries as donations and charity is rapidly decreasing as e-waste is seen more as a trade than as donations.

2.2 Governance and legislative initiatives on e-waste

Over the past three decades, a number of governance and legislative initiatives have been outlined by several countries, regional groups and international organizations to deal with the issues of e-waste around the globe. These initiatives include the Basel Convention (1989), the Bamako Convention (1998), the European Union waste electrical and electronic equipment directive (2003) and other country-specific legislation on e-waste.

2.2.1 The Basel convention

To address increasing concerns over the management, disposal and trans-boundary movement of hazardous waste, the Basel Convention on the control of trans-boundary movement of hazardous waste and their disposal was initiated in 1989 but only came into force in 1992. The principal objective of the convention is reduction of trans-boundary movement of hazardous waste and environmentally sound management for this stream of waste (SBC 1989). As of 2006, 170 states were parties to the convention with only 63 parties ratifying the 1995 amendment to the convention. The trade in hazardous waste is permissible under a mechanism of Prior Informed Consent (PIC), which requires parties to not trade in hazardous waste unless a competent authority in the importing country has been informed and consented to it. Violation by an exporter means the exporter or exporting state is responsible for re-importing the waste.

2.2.2 The Bamako Convention

Following the Basel Convention was the Bamako Convention of 1998, an agreement among African countries aimed at a complete ban into Africa imports of all forms of hazardous waste including e-waste, and environmentally sound management of such streams of waste. According to Kaminsky (1992), the convention was envisioned to address the loopholes observed by the Organization of African Union in the Basel Convention. The Bamako Convention criminalizes imports into Africa of any form of hazardous waste from developed countries and outside the continent. However, recognizing its own generation of hazardous waste and the threat of unsound management on human health and the environment at large, the continent agreed to and obliged member states to observe environmentally sound management and handling of hazardous waste. Like the Basel Convention, the Bamako Agreement allows trade in hazardous waste between African states based on the mechanism of prior informed consent.

2.2.3 European Union E-waste Directive

Stemming from the backdrop of rapidly growing amounts of WEEE in the European Union (EU) and shipment (both legal and illegal) of e-waste outside the EU states, in 2003 the EU E-waste Directive came into force in the member states and was revised in 2012. The EU disposed of an estimated 6.5 million tons of WEEE equivalent to 8% of all municipal waste with an estimated 16.3% growth rate every five years (Dalrymple *et al*. 2007). This amounts to approximately 12 million tons of WEEE to be disposed of by 2015 (Goosey 2004). The purpose of the directive is to contribute to sustainable production and consumption of EEE while improving environmental performance over the entire life cycle of EEE, and this is linked to the priority areas of prevention, reuse and recycling. The directive, which is seen as one of the most effective e-waste legislations so far, encourages member states to ensure cooperation between producers of EEE and all stakeholders in the value chain, and to promote product design that facilitates reuse, ease of dismantling and recovery of secondary raw materials. The directive in its latest version sets a minimum collection rate of 65% of all EEE put on the market. The directive obliges member states to give high priority to separation during collection and ensure prohibition of the disposal and transport of WEEE that has not undergone treatment. Further, the directive permits shipment of WEEE outside EU that must be accounted for under the obligations and targets set for collection and recovery.

2.2.4 Country-specific legislation in Africa

Despite the Basel Convention (1992), Bamako Convention (1998) and the EU Waste Electrical and Electronic Equipment Directive (2003), there still seems to be no end in sight of the flow of significant amounts of e-waste into developing countries and especially Africa. Questions have been raised about how effectively those legislations have impacted on the management of WEEE and hazardous waste in general (Ongondo *et al*. 2011). Furthermore, the seemingly non-enforceable international legislation has compelled a number of countries to domesticate international legislation and also to try to block loopholes that do not benefit their specific country. The African region, especially West Africa, is rapidly becoming the disposal hub of junk or e-waste. Nigeria leads with 110,000 tons of its 550,000 tons of secondhand imported EEE are waste (Ogungbuyi *et al*. 2012). Of the 215,000 tons of EEE imported into Ghana, 15% of the 70% imported secondhand are completely waste (Oteng-Ababio 2010). African countries, realizing the growing amount of WEEE have formulated country-specific legislation to deal with the issues of e-waste. The markets in Africa for e-waste recycling, collection and recovery of valuable fractions are controlled by a highly informalized sector using crude and rudimental methods such as manual dismantling and open burning, which release toxic chemicals with the potential of negatively impacting on human health and the environment. In order to regulate the trade, flow, management and disposal of this stream of waste, governments have introduced country-specific e-waste legislation. Ghana, Liberia, Sierra Leone and Ivory Coast are countries currently working on e-waste legislation. Notwithstanding the existing e-waste-related legislation and current management structures in these countries, and especially in Ghana, there seems to be no end in sight of e-waste management challenges, this research therefore seeks to understand the factors affecting the e-waste management.

2.3 Overview of e-waste management practices

Two main e-waste management practices are looked at in this section: extended producer responsibility (EPR) and the Best of Two World approaches in its management.

2.3.1 Extended producer responsibility

According to Lindhqvist (2000), extended producer responsibility (EPR) is an environmental protection strategy that makes the manufacturer of the product responsible for the entire life cycle of the product. The principle and trend behind EPR is reflected in several environmental policies. The aim of EPR is to relieve governments' financial burdens in managing e-waste while providing incentives for producers and manufacturers to reduce waste by reusing secondary raw materials from waste and continuously improving their products and processes. The objective of EPR in e-waste management could be achieved through the priority areas of waste preventive measures over end-of-pipe approach, enhancement of lifecycle approach, and a shift from command and control thinking to a non-prescriptive goal oriented approach (Nnorom and Osibanjo 2008). EPR seen as the most promising means to combat the increasing waste generation and pollution. It is most frequently practiced in the Organization for Economic Co-operation and Development (OECD) and member states of the EU. There is, however, very little known about the utilization and implementation in Africa and developing countries in general. Ghana in its draft proposed hazardous and e-waste bill seeks to introduce some form of EPR.

2.3.2 The best of two worlds

A significant amount of domestically generated e-waste and the e-waste exported from developed to less developed countries is handled and recycled by informal e-waste recyclers in developing countries using primitive, crude and rudimental methods, resulting in devastating threats to human health and the environment (Puckett and Smith 2002; SBC 2011). According to Wang et al. (2012), there is an urgent demand for cost-efficient treatment systems that optimally harness the valuable fractions in a more environmentally sustainable manner. Although technologies exist in developed countries to recover the critical raw metal fraction in an environmentally sustainable manner, developing countries, which are destination of the e-waste from developed nations, lack the investments, technology and infrastructure to recover the valuable fractions. The philosophy 'best of two worlds' could help less developed countries to achieve the most sustainable solution for the recovery of valuable fractions in e-waste (Reck and Graedel 2012; Wang et al. 2012). These countries could achieve this by locally pre-processing the e-waste using manual dismantling, and the transferring the complex fraction to state-of-the-art processing facilities in developed countries for further processing. Ghana, Egypt and Kenya are countries on the African continent to practice on a small scale basis some form of best-of-two-Worlds e-waste management. In these countries, complex fractions from refrigerators and cathode ray tubes (CRTs) are exported to recycling companies in Belgium after some level of manual dismantling has been completed (Manhart et al. 2014). The best-of-two-worlds approach will not only lead to detoxification and recovery of valuable materials, but also provide significantly positive revenues with minimal environmental impacts while also ensuring job creation in the informal sector (Wang et al. 2012).

2.3.3 E-waste management in developing countries

E-waste in developing countries is largely being managed by informal collectors and recyclers. Disposal options available to a user at the end of the life of a product include either adding it to household waste, giving it away or selling it to informal collectors, or donating it to a family member, school or employee. Amoyaw-Osei et al. (2011) indicated that the majority of consumers rely on informal collectors to dispose of their e-waste. E-waste collection in developing countries is done by individuals or organizations that collect and transport the respective electrical and electronic devices from the consumers to recyclers or to a disposal site, and collection and recycling are controlled largely by e-waste workers in the informal sector. Due to the lack of functional systems in developing countries, specialized hazardous waste is also sometimes disposed of by the households together with municipal waste. Institutional, corporate, commercial, industrial and household users are the typical generators of e-waste.

Repairs and refurbishment of EEE which form part of the e-waste chain in most developing countries are dominated by unregulated informal workers. The repair and refurbishing shops are also another source of e-waste. Collected discarded equipment from the sources by informal collectors or scavengers are either sold to middle men or sent directly to the various e-waste processing sites.

The formal recyclers dismantle, separate fractions and recover valuable materials from e-waste, but are also responsible for the environmentally sound treatment of the hazardous fractions. According to Amoyaw-Osei et al. (2011), about 30 tons of e-waste in Ghana was handled by formal recyclers in 2009 representing about 0.2% of the total e-waste treated in Ghana, and of this volume about 10 tons of the dismantled EEE were channeled within the downstream processing system in Ghana while the rest was treated abroad.

The informal recyclers, however, dismantle, separate fractions and recover valuable materials from WEEE without taking into account the hazardous fractions. Without using personal protective equipment but simple tools such as screwdrivers, hammers, chisels and stones, the informal recyclers dismantle and extract valuable materials from discarded EEE.

Since the introduction and implementation of the aforementioned legislation, policies and management initiatives, several studies have been conducted on the subject of e-waste. Donald (1992), on the Bamako Convention as a solution to the problems of hazardous exports to less developed countries; Krueger and Selin (2002) on the need for more comprehensive standards in the governance of sound chemical management; Gottberg et al. (2006) on producer responsibility in waste minimization and the

European Union WEEE Directive; Liu (2006) on China´s progress and the barriers in the management of e-waste; Selin and VanDeveer (2006) on improving global standards in the management of hazardous substances and e-waste in the EU; Herat (2007) on ensuring sustainable management of e-waste around the world; Kahhat et al. (2008) on the management systems of e-waste in the USA; Nnorom and Osibanjo (2008a) on the poor application of e-waste management practices and legislation in developing countries.

Shinkuma and Huong (2009) investigated the flow of e-waste into Asia and international trade policies on e-waste; Kojima et al. (2009) assessed the difficulties in applying extended producer responsibility policies in developing countries; Ni and Zeng (2009) looked at how law enforcement and global collaboration can be helpful in dealing with e-waste management; Song et al. (2012) evaluated sustainability of e-waste treatment based on energy analysis and life cycle assessment; Atasu and Subramanian (2012) investigated the implications of collective and individual producer responsibility models for e-waste take back on manufacturers; and, Zeng et al. (2013) compared e-waste management based on legislation in China and the EU.

Relating to management practices and legislation on e-waste in Ghana, a number of pioneering studies have been done. Prakash et al. (2010) assessed the socio-economic impacts and sustainable e-waste management in Ghana and Oteng-Ababio (2010) looked at e-waste as an emerging challenge to solid waste management in Ghana. Other studies include a country assessment of e-waste in Ghana by Amoyaw-Osei et al. (2011); Oteng-Ababio (2012) examined the necessity that begets the ingenuity in e-waste scavenging as a livelihood strategy in Ghana; Okolo (2013) and Kyere et al. (2013) explored e-waste management and governance structures in Accra and in Ghana as a whole.

Major concerns observed during these studies relating to e-waste management and policies include:

i. Control of e-waste dumping in developing countries

ii. Difficulties in transferring policies and technologies such as EPR in developing countries
iii. Experience of nations in e-waste management and legislation
iv. State and progress of policies and legislation on e-waste in different countries
v. Standards in e-waste management and legislation
vi. Socio-economic, health and environmental impacts of e-waste management practices

In spite of the numerous studies conducted around the world and in Ghana concerning the management and governance of e-waste, the actual factors affecting its efficient management and governance in developing countries and specifically in Ghana have not yet been examined, though some form of management and governance system exists in developing countries and also in Ghana. In this study, factors affecting the management and governance of e-waste in Ghana are identified and examined.

2.4 Impacts of e-waste activities

The complexity of e-waste is apparent in the composition and constructions of EEE. Known to exhibit hazardous characteristics (Kiddee et al. 2013; Widmer et al. 2005) and also to contain precious, critical or valuable metals (Reck and Graedel 2012; Wang et al. 2012), the proper or improper handling of e-waste involves with both positive and negative impacts. In this section, the impacts of e-waste are reviewed by highlighting the three main areas environment, health, and loss of rare earth metal resources.

2.4.1 Environmental impacts of e-waste

The bulk of e-waste ends up dumped in municipal landfills or shipped (legally or illegally) to developing countries, where primitive, crude and rude processing or recycling methods are used to recover or retrieve valuable fractions. With e-waste containing significant amounts of toxic or hazardous chemicals such as mercury (Hg), lead (Pb), arsenic (As), cadmium (Cd), brominated flame retardants, and polychlorinated biphynels, in un-engineered landfills these could leach into soil, surface and ground water causing serious environmental damage to crops and aquatic and human life (Huo et al. 2007). According to Brigden et al. (2005) and Puckett and Smith (2002), Guiyu in China is one of the world's most popular destinations for disposal and processing of e-waste, and presents a good example of how the environment is threatened by the primitive recycling and disposal methods.

The practice of manual dismantling using hammers and stones and open-air-burning of e-waste has the potential of releasing several toxins and hazardous chemicals including carcinogens and neurotoxins (e.g., dioxins and furans) into the air, soil and water. The vaporization of volatile substances into the atmosphere during burning also presents a threat to the environment. According to Kiddee et al. (2013), the release of toxic contaminants into soil, water and air as a result of improper disposal of e-waste could impact on human health through the local food chain and directly on the workers.

Despite the difficulties in previous studies to clearly associate environmental pollution with recycling of e-waste, recent studies however confirm the existence of causal evidence that there is a strong relationship between environmental pollution and e-waste (Sepúlveda et al. 2010; Caravanos et al. 2011). Studies have revealed contaminant levels higher than the minimal allowable traces permitted in soil and water. Wong et al (2007b); Wong et al. (2007a); Spalvins et al. (2008); Fu et al. (2008); Leung et al. (2008); Lu et al. (2009); Ha et al. (2009); Jun-hui and Hang (2009), discovered concentrations of trace metals in soil, water and plants in areas of e-waste processing.

Although not much research has been done on the heavy metals from e-waste processing and disposal sites and their impacts on the environment in Ghana, studies so far have shown significant heavy metal concentrations from e-waste disposal sites in the country. Asante et al. (2012) revealed traces of arsenic (As) in e-waste recycling workers in Agbogbloshie, Atiemo et al. (2012) found heavy metal contamination of surface dust from e-waste recycling sites in Ghana, and Otsuka et al. (2012), examined heavy metal contamination around the e-waste recycling and disposal site in Agbobloshie. These studies identified heavy metals such as Pb, Hg, Ni, Cd, Cu and As in soil and water within e-waste disposal and processing sites.

Also recorded are organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and brominated flame retardants (BFRs), which also impact on the environment and human health. It is however, worth noting that banned substances such as PCBs, which were banned in the USA in 1975 due to their cancerous nature and the fact that they remain in the environment for a long time, are still measured at e-waste disposal sites in Ghana and China. Asante et al. (2011), in analyzing human exposure to PCBs, PBDEs and hexabromocyclododecanes (HBCDs) in Ghana, pointed to an increasing trend of these pollutants to be observed in human breast milk.

2.4.2 Health impacts of e-waste

According to Brook et al. (2004), there is a growing epidemiological and clinical evidence of the increasing adverse effects of ambient air pollution on health. The combustion of e-waste materials to recover valuable fractions has the potential of releasing fine particulate matter into the atmosphere which when inhaled, ingested or by dermal contact and can cause pulmonary, cardiovascular and respiratory diseases. Grant et al. (2013) indicate the potential of some of these hazardous substances and heavy metals (Table 2) to cause cancer in humans and animals. Levels of PCBs, BFRs and other hazardous components measured in e-waste processing sites in China, Nigeria, India and Ghana have been seen to be over the acceptable or allowable limits in the environment. Further, measurements of these toxic substances in human blood (Huo et al. 2007), serum or human hair (Leung et al. 2008), urine (Asante et al. 2012) and even in cow and human breast milk have also been revealed to be above the allowable or acceptable limits. Particulate matter of pollutants less than 2.5 µm were measured within the e-waste processing site in Guiyu, China, which exceeded the USEPA ambient air quality standards.

Besides the inhalation, ingestion and dermal intake of particulate matter from e-waste recycling sites is exposure of humans to dioxins and furans. Reports indicate significantly high amounts over the acceptable limits of dioxin (PCBD & BFRs) in human hair.

Sepúlveda et al. (2010) measured PCDD in human hair that ranged between 16.4 and 25.6 pgg^{-1}, which Leung et al. (2007) indicated was 29-466 times higher than the polychlorinated dibenzodioxin (PCDD) level in people exposed to ambient air in Japan. The amounts of dioxins and furans as reported by Sepúlveda et al. (2010); Leung et al. (2007) and Leung et al. (2006) can cause irritation of the eyes, nose and throat (Chen et al. 2011). Studies in an e-waste recycling site in Vietnam revealed PBDEs (between 20-250 ngg-1 lipid wt) and HBCDs (1.4-7.6 ngg^{-1} lipid wt) in breast milk that were significantly higher than at reference sites in Hanoi (Tue et al. 2010). Estimates by Tue et al. (2010) revealed further that infants' intake of PBDEs in breast milk of some occupational mothers involved in e-waste recycling were close to or higher than the USEPA standards.

Further components of e-waste critical to human health are heavy metals such as Pb, Ni, Cd, Cr, Hg, and As released as a result of manual dismantling, open-air-burning and improper disposal of e-waste. Heavy metals are well known or suspected to have developmental neurotoxicity in humans especially children (Chen et al. 2011). Intelligence quotient, memory loss, language, gross and fine motor skills, attention, executive function and behavior have been observed as some effects of neuro-developmental deficits caused by excessive intake of trace metals (AAP, 2003). In China especially, numerous studies have been done to determine the risk of cancer from the inhalation, ingestion and through dermal contact of these heavy metals for workers and people within the e-waste processing sites (Leung et al. 2006; Fu et al. 2008; Zhao et al. 2008; Xing et al. 2009; Leung et al. 2010; Frazzoli et al. 2010). This is however not the case in developing countries, where in the recycling or management of e-waste there are little or no regulations guiding the activities of the workers or stakeholders involved. Knowledge on the spatial extent of the impacts from e-waste activities in terms of contamination assessment and the health risk could guide future policy formulation and assist in planning remediation measures. This research focuses on assessing the spatial extent of impacts from e-waste activities within the disposal site Agbogbloshie inAccra, Ghana.

2.4.3 Economic impacts of e-waste

In this section, attention is paid to the employment avenues along the e-waste chain and also to the resources or critical raw materials that are lost due to improper handling, recycling and management of e-waste.

Poverty, employment and e-waste

The entire chain of e-waste involves the consumption (distributors, repairer and refurbishers), collection (aggregation and diversion of e-waste stream to treatment facilities), recovery and recycling where the toxic and valuable substances are separated followed by pre-processing and end processing (final stage to refine and detoxify e-waste), and finally the disposal stage (Wang *et al*. 2012). Each stage in the chain is expected to be a source of either formal or informal sector employment, employing millions of people around the world. In the developed countries, the jobs created in the e-waste chain are mostly handled by a well-regulated formal sector, while in developing countries the majority of the employment created in the e-waste chain is handled by an unregulated informal sector. Studies in some developing countries, i.e. Ghana, (Prakash et al. 2010), Nigeria (Manhart et al. 2011), Kenya (Mureithi and Waema 2008) and India (Williams et al. 2008; Wath et al. 2011) have shown the contribution of e-waste-related business to employment and subsequently the wider economic impact to their nations and reduction of poverty in these countries.

Sustainable management of the e-waste stream not only safeguards the environment and human health from the hazards posed by the rising levels of e-waste but can also serve as an avenue to create employment and combat poverty (UNEP 2006). According to Seligson (2013), in most of stages in the e-waste chain the poor and marginalized are employed in places where the activities take place. In Kenya, the e-waste sector creates employment for both formal and informal workers with vendors in the informal sector making the equivalent of $3 dollars a day, which is above the World Bank poverty benchmark of one dollar. In India and Delhi alone, a shutdown of e-waste recycling activities means close to 25,000 people with their dependents losing their jobs and source of livelihood (Forge 2007). Prakash et al. (2010) estimate that between 4,500 to 6,000 people are involved in the e-waste recycling activities in Accra alone with an assumption that 7,000 to 36,000 people in Accra are thriving partially or fully dependent on e-waste collection and recycling activities.

Further estimates suggest between 87,000 and 126,000 people in Accra alone are sustained by the e-waste recycling sector (Prakash et al. 2010). Based on estimates by Prakash et al. (2010), between $105 and $268 million per annum is created by refurbishing and recycling sectors with recycling sector treating between 10,000 and 13,000 metric tons of e-waste. Despite the estimated contribution the sector could make to the national economy, this is not reflected in the national budget due to the widespread informality that means this sector is not included in the national taxation system in Ghana.

E-waste and rare earth metals

Rare earth metals are metals which are not widely known because they are low in the production chain and critical to hundreds of high tech applications (Hurst 2010). Both rare and precious metals are seen as critical components in the world's modern day technology and non-availability would make some applications impossible. According to the US Department of Energy (2011), rare earth and precious metal resources are essential in mobile phone technologies, laptops, defense industries (cruise missiles, precision-guided ammunition, radar systems, reactive armors). Their report indicates the usefulness of these resources in green technologies such as generation in wind-powered turbines, hybrid vehicles and as catalyst in oil refineries. Over the past years, China has historically been known to control 97% of world's rare earth metals market. This is, however, expected to change. Based on data from the US Geological Survey (USGS) rare earth report, regarding deposits or reserves, Brazil is ranked first (32%), second (22%), the Commonwealth Independent States (CIS) third (12%), Vietnam fourth (9%), Australia fifth (8%), and the United States sixth (7%).

The wide application of these metals in modern day technology has consequently caused an increase in demand and production of these metals. The important role primary production (mining) in the supply for many electrical and electronic and modern day technological devices cannot be overlooked. According to Rademaker et al. (2013), notwithstanding the contribution of mining in the supply of critical raw materials, the footprint of the mining of these metals cannot be ignored. According to Schluep et al. (2009), mining requires a considerable area of land with operations causing water and air pollution as well as land degradation. Furthermore, exploitation is associated with the release of or exposure to radioactive elements, which have negative implications for human health (Rademaker et al. 2013). Schluep et al. (2009) reveal that the mining of rare earth metals and precious metals contributes to significant CO_2 emissions. The authors state that production of one ton of gold, palladium or platinum generates CO_2 emissions of about 10,000 tons.

With depleting rare earth and precious metal resources, increasing destruction of virgin land, pollution to water and air as a result of mining, proposals have been intensified to consider proper recycling and overall management of WEEE, which is seen as the fastest stream of waste and regarded as a waste problem. With modern electrical and electronic equipment, however, containing up to 60 different elements many of which are valuable and some toxic, the resource impact of e-waste as a source of critical and precious raw material needs to be focused on. According to Rademaker et al. (2013), a number of countries spearheaded by the OECD countries have put in place legislation and strategies to secure country-specific and global supplies of these metals so as to decrease their dependency on China, one of the main suppliers of rare earth metals. These strategies include the proposal of efficient e-waste recycling to recover the metals for reuse.

Over 500 million computers in 1997 alone became obsolete, and in 2007, 130 million mobile phones were also discarded resulting in about 65,000 tons of mobile phone waste in the USA (UNEP 2005). In Japan, 2010 saw about 610 million mobile phones discarded. With mobile phones containing 40 different elements, estimates by Schluep et al. (2009) indicate that from a ton of mobile phones without batteries, efficient recycling can recover 3,500 g of Ag, 340 g of Au, 140 g of Pd and 130 kg of Cu. With Gartner's (2007) estimate of 1.2 billion mobile phones sold in 2007, it is expected that higher amounts of critical and precious metals can be extracted in an efficient recycling system. With WEEE regarded as a problematic waste stream which can cause serious health and environmental damage if not properly handled, Schluep et al. (2009) and Hurst (2010) agree that e-waste could be an enormous source of critical and precious metals. This not only provides an alternative to mining but ensures among others, a continuous supply of critical metals and efficient and sustainable management of e-waste.

Although, several studies indicate the enormous economic impacts such as employment and livelihood provision along the e-waste chain in both developed and developing countries, critical raw materials which could also be recovered have not yet been examined. It is in this regard that this study seeks to examine the critical raw materials that are lost due to the informal recycling of e-waste in Ghana.

2.5 Environmental and health risk assessment

This section takes a look at the indices and models used for the assessment of environmental and human health risks from contamination sites.

2.5.1 Environmental risk assessment

The past few decades have seen different heavy metal assessment indices applied to heavy metals in soils, and each of these indices has its strengths and weaknesses. Some are capable of aggregating contaminants into a unit for the purpose of comparison, while others are only meant for single element assessments. Caeiro et al. (2005) categorizes the indices into:

i. Contamination indices
ii. Background enrichment indices
iii. Ecological risk indices

Contamination indices

This index compares the contaminants with clean and or polluted stations measured in the study area or simply aggregates the metal concentrations. It allows the identification of priority contamination sites for implementation of decontamination actions and requires several measurements in the same sampling location. It does not allow threshold classification from unpolluted to highly polluted. Examples of these types of index are as follows:

a) Ott (1978) calculated the pollution index as:

$$\boldsymbol{PI = \sum_{i-1}^{n} W_i C_i} \qquad \text{Equation 2.1}$$

where PI is the pollution index, W_i is weight for pollution variable and C_i the highest concentration of the pollution variable $_i$ reported in a location of interest. For each pollutant $_i$, the weight is based on the reciprocal of the median of observed concentrations.

b) The metal enrichment index was calculated as shown by Riba et al. (2002) as;

$$\boldsymbol{MEI = \frac{C_I - C_o}{C_o}} \qquad \text{Equation 2.2}$$

where C_I is the total concentration of each metal measured in the sediment, C_0 the heavy metal background level established for the ecosystem studied. For the present study, contamination indices were avoided for two main reasons. First, a suitable location could not be found for background concentration values. Identifying such location requires prior information of the site including activities previously undertaken at the location to avoid choosing a contaminated site. There is also no published data indicating pre-industrial concentrations of the metals of interest for a contamination index to be calculated. The second reason is that it would have been necessary to compare the results obtained to those of similar studies elsewhere, but the contamination index does not lend itself to such comparisons. The fact that contamination indices are not summative in character provided a further disincentive for their use in the present study.

Background enrichment indices

Background enrichment indices are used to compare the measured contaminant levels with different reference levels available in literature that can be used for any study area. The background indices consist of single indices or indicators used to calculate only one metal contamination, while others are summative or average indices that are used to calculate more than one metal contamination at a site (Caeiro et al. 2005; Qingjie *et al*. 2008). These indices are described below:

a) Enrichment factor: The enrichment factor (EF) can be used to differentiate between metals originating from human activities and those in the natural background and to assess the degree of anthropogenic influence. The EF of an element X(EFx) in a sample with respect to natural abundance is calculated as follows:

$$\boldsymbol{EF_X} = \frac{\lfloor X/E_{(ref)} \rfloor_{sample}}{\lfloor X/E_{(ref)} \rfloor_{crust}} \qquad \text{Equation 2.3}$$

where X is the concentration of the heavy metal of interest, and $E_{(ref)}$ is the reference element for normalization (Meza-Figueroa et al. 2007). The elemental concentration in the crust used in this study is the average continental crust data (Bowen 1979; Taylor and McLennan 1985). Contamination on the basis of enrichment factors are grouped into five categories (Table 2.3).

Table 2.2: Enrichment factor and categories of enrichment

Enrichment factor (EF)	**Intensity of enrichment**
EF < 2	Deficiency to minimal enrichment
2 ≤ EF < 5	Moderate enrichment
5 ≤ EF < 20	Significant enrichment
20 ≤ EF < 40	Very high enrichment
EF > 40	Extremely high enrichment

Source: Kartal et al. (2006)

For the present study, however, the enrichment factor was not used because it was difficult to identify an element for normalization, as e-waste and other scrap metals that are worked on at the sampling site contain all the elements that were earmarked for normalization at the start of the study.

b) Index of geo-accumulation (I_{geo}): Muller (1969) originally defined this Index to determine metal contamination or metal accumulation in sediments (Banat *et al*. 2005) by comparing actual concentrations with pre-industrial levels. It has been found to be very useful in evaluating metal deposits in soils (Yu et al. 2011; Amuno 2013), and has the advantage of using any background concentration to compared levels with those of studies elsewhere. The index is however not summative, and as such does not give a comprehensive picture of a particular site, but it is also very suitable for evaluating single elements. The index can be expressed as:

$$I_{(geo)n} = \log_2\left(\frac{C_n}{1.5B_n}\right) \qquad \text{Equation 2.4}$$

where Cn is the measured concentration of the heavy metal in the soil sample, and Bn is the geochemical background concentration of the heavy metal (crustal average) (Taylor and McLennan 1985). The factor 1.5 takes care of possible variations in background values for a given metal in the environment as well as very small anthropogenic influences (Ghrefat and Yusuf 2006). The index (I_{geo}) is grouped into seven categories by Muller (1969) as shown in Table 2.4.

Table 2.3: Classification of index of geo-accumulation

Category	**I_{geo} range**	**Pollution or contamination intensity**
0	$I_{geo} \leq 0$	Uncontaminated
1	$0< I_{geo}\leq 1$	Slightly contaminated
2	$1< I_{geo} \leq 2$	Moderately contaminated
3	$2< I_{geo}\leq 3$	Moderately severely contaminated
4	$3 <I_{geo}\leq 4$	Severely contaminated
5	$4< I_{geo}\leq 5$	Severely extremely contaminated
6	$I_{geo} >5$	Extremely contaminated

This research makes use of the index of geo-accumulation to assess and evaluate the rare earth and critical metals owing to its non-summative nature.

c) Contamination factor and degree of contamination

The contamination factor and the degree of contamination have been used over the years to assess the extent of contamination of heavy metals in soil (Loska et al. 1997; Loska et al. 2004; Liu et al. 2005; Atiemo et al. 2012). The contamination factor is expressed as:

$$\boldsymbol{C_f^i = \frac{C_{0-1}^i}{C_n^i}} \qquad \text{Equation 2.5}$$

where C_f^i is the contamination factor of the element of interest, C_{0-1}^i is the concentration of the element in the sample, and C_n^i is the background concentration or the continental crustal average as was used by Taylor and McLennan 1985). The contamination factor is defined according to four categories (Table 2.4).

Table 2.4: Classification of contamination factor (CF)

Contamination factor	**Extent of contamination**
CF < 1	Low contamination
1< CF ≤ 3	Moderate contamination
3< CF ≤ 6	Considerable contamination
CF>6	Very high contamination

Although the contamination factor is used to evaluate the pollution of the environment by single substances, it is complimented by the degree of contamination, which is the sum of contamination factors and describes the contamination of the environment by all examined substances. The degree of contamination (C_{deg}) defines the quality of the environment and is expressed as:

$$\boldsymbol{C_{deg} = \sum C_f^i} \qquad \text{Equation 2.6}$$

The degree of contamination was useful in this study, as it gives a comprehensive assessment of contamination by summing up contamination factors of all elements measured and the possibility of utilizing background concentrations. The degree of contamination is useful to identify hot spots within the sampling location. It is grouped into four categories (Table 2.5).

Table 2.5: Categories of degree of contamination

Degree of contamination (C_{deg})	**Extent of contamination**
$C_{deg} < 8$	Low degree of contamination
$8 \leq C_{deg} < 16$	Moderate degree of contamination
$16 \leq C_{deg} < 32$	Considerable degree of contamination
$C_{deg} \geq 32$	Very high degree of contamination

Ecological risk index

The ecological risk index compares the contaminants with the soil quality guidelines values (SQG), and quantitatively expresses the potential ecological risk of a given contaminant. The strength of this index lies in the fact that it is summative and is capable of explaining the underlining ecological risks associated with a contaminated site. The ecological risk index is expressed as:

$$\boldsymbol{E_R^i = T_r^i \times C_r^i} \qquad \text{Equation 2.7}$$

where E_R^i is the ecological risk factor, C_r^i is the contamination factor (Equation 2.5), and T_r^i is the toxic response factor provided by Hakanson (1980). The toxic response factor T_f^i for Zn, Cr Cu, Pb, Cd and Hg is given as 1, 2, 5, 5, 30 and 40, respectively (Hakanson 1980; Qingjie *et al*. 2008; Sun *et al*. 2010; Amuno 2013). The ecological risk factor is grouped into five categories (Hakanson 1980) (Table 2.6).

Table 2.6: Categories of ecological risk factors

Ecological risk factors ($\boldsymbol{E_R^i}$)	**Category**
$E_R^i < 40$	Low ecological risk
$40 \leq E_R^i < 80$	Moderate ecological risk
$80 \leq E_R^i < 160$	Considerable ecological risk
$160 \leq E_R^i < 320$	High ecological risk
$E_R^i \geq 320$	Significantly high ecological risk

The summation of the ecological risk factors of each element gives the potential ecological risk index and is expressed as:

$$\boldsymbol{R_i} = \sum_{i-1}^{n}(\boldsymbol{E_r^i}) \qquad \text{Equation 2.8}$$

The potential ecological risk index is grouped into four categories by Hakanson (1980) (Table 2.7).

Table 2.7: Categories of potential ecological risk index

Potential ecological risk index($\boldsymbol{R_i}$)	**Category**
R_i < 150	Low potential ecological risk
150 ≤ R_i < 300	Moderate potential ecological risk
300 ≤ R_i < 600	High potential ecological risk
R_i ≥ 600	Significantly high potential ecological risk

2.5.2 Human health risk assessment

People are exposed to a variety of harmful chemicals in the air they breathe, food they eat and products that come in contact with their skin. Exposure is the contact between an individual and a chemical agent over a defined period. According to McKone and Daniels (1991), human beings are exposed to toxic chemicals via inhalation, ingestion and dermal contact. To assess the potential health effects of a heavy metal in sites such as the e-waste processing and disposal sites, it is important to determine the risk of exposure based on:

i. The toxicity of the chemicals in the analysis by the three routes of exposure
ii. The levels of exposure to those chemicals.

In toxicological risk assessments for non-carcinogenic toxicants, a reference dose (RfD) or tolerable daily intake (TDI) ranging from zero (0) to a finite value is assumed to be tolerated by the organism with low or no probability of expression of the toxic effects. The potential of a chemical to cause harmful effects in an exposed individual is termed hazard, whereas the probability of the harmful effect occurring is known as risk. Hence, if the daily dose intake exceeds the reference dose then the organism is considered to be at potential risk. According to Ferreira-Baptista and De Miguel (2005) it is likely at this point that the organism will show signs of acute exposure to the chemical. The assessment of exposure of children to heavy metals was conducted based on the model developed by the USEPA (1996). The document defines the guidelines and screening levels for contaminants in soils in urban exposure scenarios. There are five basic underlining assumptions made in the model which are applicable for the purpose of this study:

i. Children are exposed to chemicals or contaminants through ingestion, inhalation of dust particles and dermal contact.
ii. Intake rates and particle emission factors for contaminants can be approximated by those developed for soil.
iii. Biometric and exposure parameters of children in Accra are similar to those of children in the USA.
iv. The overall non-cancer risk experienced by a child can be computed for each element by summing the individual risk calculated for each exposure pathway.
v. For carcinogens, exposure to street dust is quantified as a lifetime average daily dose, i.e. the weighted average of the exposure experienced by an individual as a child and as an adult.

Exposure is expressed in terms of daily dose intake, which is calculated separately for each element and for each exposure pathway. The dose intake through inhalation of contaminants [$D_{(inh)}$ $(mg/kg/day)$] is expressed by the relation:

$$\boldsymbol{Dinh = C(mg/kg) \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT}} \qquad \text{Equation 2.9}$$

where PEF is the particulate emission factor (m^3/kg), InhR is the inhalation rate (m^3/day), EF is the exposure frequency (d/y), ED is the exposure duration (years), BW is the body weight (kg), AT is the averaging time (days), and C is the concentration of elements in the sample.

The dose intake by dermal contact [$D_{(derm)}$ $(mg/kg/day)$] is expressed as:

$$\boldsymbol{Dderm = C(mg/kg) \times \frac{SA \times SL \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6}} \qquad \text{Equation 2.10}$$

where SA is the exposed surface area (cm^2/day), SL is the skin adherence factor ($mgcm^{-2}day^{-1}$), ABS is the skin absorption factor, EF is the exposure frequency (d/y), ED is the exposure duration (years), BW is the body weight (kg), AT is the averaging time (days), and C is the concentration of elements in the sample.

The dose intake by ingestion [$D_{(ing)}$ $(mg/kg/day)$] of dust particles is given by:

$$\boldsymbol{Ding = C(mg/kg) \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6}} \qquad \text{Equation 2.11}$$

where C is the concentration of elements in the sample, IngR is the ingestion rate (mg/day), EF is the exposure frequency (d/y), ED is the exposure duration (years), BW is the body weight (kg), and AT is the averaging time (days). To further determine the non-cancer risk if exposed, the following relation was used:

$$\boldsymbol{HQ = \frac{DI}{RfD}} \qquad \text{Equation 2.12}$$

where HQ is the hazard quotient for a particular route of exposure, DI is the dose intake by a given route of exposure, and RfD is the reference dose for a particular element through a particular exposure pathway. The values of the reference dosage for each element and per exposure pathway are listed in Table 2.9. The RfD for inhalation-specific toxicity data are available for Ba, Cd, Co, Cr and Ni. For Co and Cr, and values are available for both cancer and non-cancer risks (Table 2.10). For Cu, Hg, Pb and Zn, the toxicity values considered for the inhalation route are the corresponding oral or ingestion reference doses and slope factors, with the assumption that after inhalation the absorption of the particle-bound toxicants will result in similar health effects as if the particles had been ingested (Van den Berg 1995; Ferreira-Baptista and De Miguel 2005). To determine the overall exposure risk through the three exposure pathways, the hazard index expressed by Equation 2.13 was applied:

$$\boldsymbol{HI = HQ(inh) + HQ(ing) + HQ(derm)} \qquad \text{Equation 2.13}$$

where HI is the hazard index, and HQ (inh, ing and derm) represents the hazard quotients for inhalation, ingestion and dermal pathways of exposure, respectively.

Table 2.9: Guidance values for the determination of dose intake

Symbol	Definition	Value
IngR	Ingestion rate (mg/day)	200
EF	Exposure frequency (d/y)	350
ED	Exposure duration child (years)	6
BW	Body weight child (kg)	15
AT	Averaging time (days)	ED×365
PEF	Particulate Emission Factor (m^3/kg)	1.316×10^9
InR	Inhalation rate child (m^3/day)	10
SA	Exposed surface area (cm^2/day)	2800
SL	Skin adherence factor ($mgcm^{-2}day^{-1}$)	0.2
ABS	Skin absorption factor	0.1

For carcinogens, the lifetime average daily dose (LADD) for inhalation exposure was used in the assessment of the cancer risk (USEPA 1989; Franklin 2000). The LADD is expressed as:

$$\boldsymbol{LADD} = \frac{\boldsymbol{C \times EF}}{\boldsymbol{AT \times PEF}} \times \left[\left(\frac{\boldsymbol{InhR_{child} \times ED_{child}}}{\boldsymbol{BW_{child}}}\right) + \left(\frac{\boldsymbol{InhR_{adult} \times ED_{adult}}}{\boldsymbol{BW_{adult}}}\right)\right] \qquad \text{Equation 2.14}$$

The potential cancer health risk was obtained by the product of the lifetime average daily dose and the inhalation slope factors for each of the heavy metals (Table 2.9).

Table 2.10: Heavy metal RfD for different exposure pathways

Metal	Ingestion	Dermal contact	Inhalation, non-cancer risk	Inhalation, cancer risk
Ba	7.0×10^{-2}	4.9×10^{-3}	1.43×10^{-4}	
Cd	1.0×10^{-3}	1.0×10^{-5}		6.3×10^{0}
Co	2.0×10^{-2}	1.6×10^{-2}	5.71×10^{-6}	9.8×10^{0}
Cr	3.0×10^{-3}	6.0×10^{-5}	2.86×10^{-5}	4.2×10^{1}
Cu	4.0×10^{-2}	1.2×10^{-2}		
Hg	3.0×10^{-4}	2.1×10^{-5}		
Ni	2.0×10^{-2}	5.4×10^{-3}		8.4×10^{-1}
Pb	3.5×10^{-3}	5.25×10^{-4}		
Zn	3.0×10^{-1}	6.0×10^{-2}		

2.6 Formal and informal e-waste management

E-waste management as has already been indicated continues to be a growing environmental and financial problem in Ghana and other developing countries (Van de Klundert and Lardinois 1995). The management of waste in general has traditionally been the responsibility of municipal governments. However, the inadequacies of most municipal governments to manage and handle waste in most developing countries has necessitated the involvement of private, formal, informal and community-based groups to participate in the management of waste in general and specifically e-waste. In Ghana like many other developing countries, the e-waste management sector is largely controlled by informal sector actors with the formal sector taking up a small share of the e-waste market. Ghana is known to have an efficient collection system (collecting up to 97% of e-waste) largely due to the highly informalized participation of the private sector, which contributes to about 80% to collection and recycling of e-waste (Amoyaw-Osei et al. 2011). The informal sector is known to be unregistered and unregulated, and the primitive methods of operation are shown to be environmentally unsustainable and pose a threat to human life. Chi et al. (2011), on a sector review of China´s informal e-waste recycling, indicated that the informal e-waste recycling activities are not only associated with serious health and environmental impacts but also a supply deficiency to formal recyclers and inefficient recovery of critical raw materials inherent in e-waste.

In contrast, the formal sector recyclers are known to be regulated and registered, and employ environmentally sound technologies to manage e-waste, thereby minimizing the threat hazardous fractions contained in e-waste pose to environment and human life while maximizing the benefits inherent in e-waste. These recyclers have large-scale investments in infrastructure, and the ability to internalize environmental costs and control detoxification. Despite the effectiveness of the formal sector, it is however out competed by the informal sector operators who dominate the e-waste management sector, have active strong networks, employ very cheap labor and are able to access areas, communities and door to door collection of e-waste paying for the waste they collect (Amoyaw-Osei et al. 2011; Chi et al. 2011; Ciocoiu and Täriu 2012; Oteng-Ababio

2012). With a growing e-waste industry, the economic and livelihood issues attached to e-waste and the recovery of valuable metals, both formal and informal actors continue to enter into the management of this stream of waste. It is however clear that most of the formal players are unable to gain the e-waste due to the competition from the informal actors.

To ensure environmentally sustainable management of e-waste in Ghana and in developing countries in general, the strength of the informal sector in collection of e-waste and their strong active network vis à vis. the improper or unconventional methods employed by them as well as the capacity of the formal sector to process e-waste in an environmentally sustainable manner vis à vis their inability to compete for the collection of e-waste need to be understood. This research, therefore, seeks to identify and examine options for bridging the gap between the formal and informal sectors in e-waste management, and to suggest a framework to integrate the formal and informal sectors using stakeholder mapping, field observations, analysis of the e-waste chain, interviews, and review of literature on formalizing informal sectors.

2.7 Geostatistics and spatial distribution

Recent times have seen a lot of attention paid to spatial distribution and assessment especially of heavy metals in soil. According to Goovaerts (1999), the uniqueness of soil and heavy metal contamination in soil lies in the fact that it is related to location in space and time, and as such assessment and analysis of soil and heavy metal contamination should account for either one or both of these aspects. While previous studies in soil and heavy metal distribution lacked information on unsampled locations, the introduction of geostatistics, which incorporate spatial and temporal tools coupled with capabilities such as semivariograms and kriging, help to describe spatial patterns and predict contaminants at such unsampled locations (Warrick *et al*. 1990; Goovaerts 1998). Additional tools incorporated into geostatistics make it further possible to assess uncertainty about soil quality, soil pollutant concentrations, to simulate spatial distribution of attribute values, and to model space-time processes (Goovaerts 1999).

ArcGIS, R statistical package and Spacestats are the most commonly applied packages with geostatistical capabilities. With their strength regarding assessment of heavy metals and other soil pollutants, there have been a number of pioneering studies utilizing the capabilities of geostatistics and spatial distribution. Jerrett et al. (2005) used geostatistics to spatially analyze air pollution and mortality data. Numerous researchers have made contributions on geostatistics and spatial distribution with a focus on soil and heavy metal pollution (Cambardella et al. (1994); Goovaerts (1998); Goovaerts (1999); Cattle et al. (2002); Korre et al. (2002); Imperato et al. (2003); Xing et al. (2005); Liu et al. (2006); Shi et al. (2007); Lim et al. (2008); Hoek et al. (2008); Sun et al. (2010); Bai et al. (2011) and Guo et al. (2012)).

In Ghana, using geostatistics Veihe (2002) evaluated the spatial variability of potential soil erodability and its relation to soil type. In a study in the Amansie West District of Ghana, Duker et al. (2006) revealed an association between arsenic in the soil and spatial distribution of the Buruli Ulcer. Otchere (2004); Kumi-Boateng (2007) and Adjei-Boateng et al. (2010) applied geostatistical methods to examine heavy metal pollution in soil within the mining areas and river sediments in Ghana. The major findings show that geostatistics are able to describe spatial patterns, interpolate data, integrate secondary data to give reliable predictions, create maps of the probability, and create maps of the error of estimation, and also support decision makers in making informed decisions about the reliability of maps. Although several studies conducted using geostatistical capabilities and revealing it strength and advantages over the traditional non-spatial statistical method, the application of geostatistics and the concept of spatial distribution has not yet been utilized in the assessment of heavy metal pollution from e-waste disposal sites in Ghana. Geostatistics are therefore used in this study to determine the spatial distribution, pattern and structure of the heavy metal contaminants within the study area.

3 MATERIALS AND METHODS

3.1 Study area

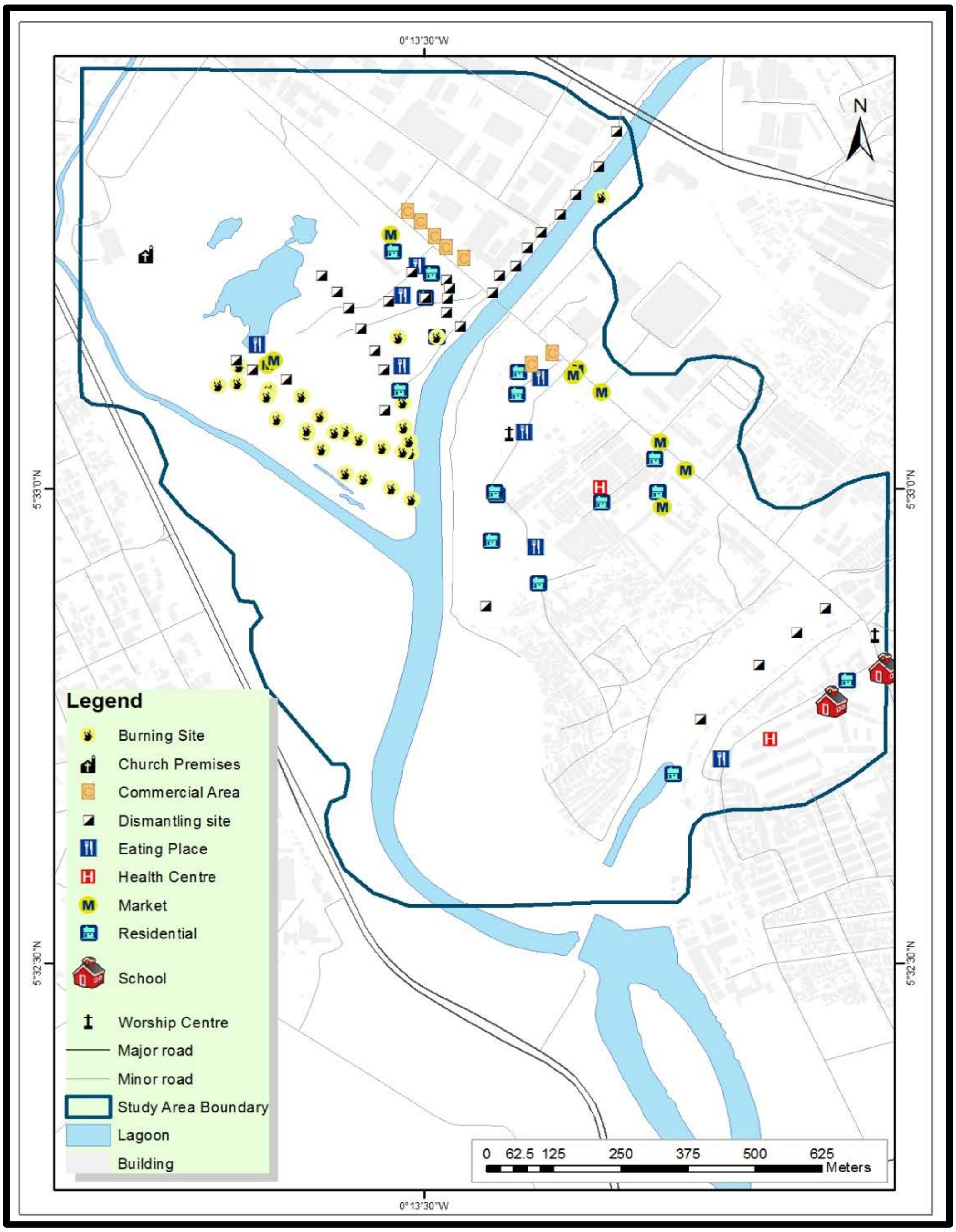

Figure 3.1: The Agbogbloshie e-waste processing site in Accra and its surroundings

3.1.1 Location, size and climate

The study area is the Agbogbloshie scrap yard (Figure 3.1) and its surroundings in the Greater Accra region of Ghana. For the purpose of this study, the study area shall be referred to as the Agbogbloshie e-waste processing site (AEPS). The AEPS is situated on the banks of the Odaw River and the Korle Lagoon northwest of the Central Business District of the national capital between latitudes 5° 32’ 30’’N and 5° 33’ 30’’ N and on longitude 0° 13’ 30’’W.

The AEPS covers an area of approximately 6.2 ha. The Accra Metropolitan Assembly which hosts the AEPS, shares boundaries in the south with the Gulf of Guinea, in the east with La Dade Kotopon and Ledzokuku municipalities, in the north with Ga East and Adenta Municipalities, and in the west with Ga Central and Ga South Municipalities. The AEPS is also known to be the hub and largest e-waste processing site in Ghana.

The AEPS lies within the savanna zone with two rainy seasons and an annual rainfall average of 730 mm during the rainy periods. The zone has fairly uniform temperatures ranging from a monthly mean of 24.7°C in August (coolest) to 28°C in March (hottest) and an annual average of 26.8°C. Accra is close to the equator with very uniform daylight hours during the year and in general high relative humidity ranging from 65% at midday to 95% at night. Winds are mainly west-south-west to north-east with a wind speed ranging from 8 to 16 km/hr.

3.1.2 Geology

The geology of the study area consists of precambrian dahomeyan schist, granodiorites, granites gneiss and amphibolite as well as late precambrian togo series comprising mainly quartzite, phillites, phylitones and quartz breccia. The Paleozoic Accraian sediments sandstone, shale and interbedded sandstone-shale with gypsum lenses are also present. According to Keelson (2014), the geology of the area gives rise to generally lateritic soil groups, which are easily erodible and provide a significant source of sediment.

3.1.3 Soil and vegetation

According to Keelson (2014), the soils within the area can be divided into four main groups:

i. drift materials resulting from deposits by wind-blown erosion
ii. alluvial and marine mooted clays
iii. residual clays and gravels from weathered gneiss and schist rocks
iv. lateritic sandy clay soils.

The city lies in three broad vegetation zones: shrubland, grassland and coastal land. The coastal land consists of wetland and dunes. The AEPS falls within the coastal wetland zone, which is a productive and important habitat for marine life. Earmarked in 2003 for the Korle Lagoon ecological restoration zone, AEPS has been taken over by e-waste processing and disposal activities.

3.1.4 Demographics and occupations

In 2010, the population of Accra was 1,848,614 (GSS 2010)with AEPS having 40,000 inhabitants who are mainly Ghanaians and other foreign nationals from West Africa. Although the indigenous ethnic group within the city and the AEPS is Ga, Oteng-Ababio (2012) however indicates that most of the inhabitants or workers within the AEPS are migrants from the northern part of Ghana. Despite the varied age group within the AEPS, the workforce is mostly young between 15 and 35 years. Caravanos et al. (2011) identified children as young as 11 years involved in the e-waste activities. Prakash et al. (2010) and Amoyaw-Osei et al. (2011) showed that e-waste and scrap processing as well as foodstuffs trading are the main occupations in the AEPS. Prakash et al. (2010) estimated close to 200,000 livelihoods dependent on e-waste recycling activities in the AEPS alone, which employs between 4500 and 6000 people. Observations made during fieldwork in this study showed that some workers stay on site of their working environment with their families while others live 100 m across the Odaw River in the informal settlement called Sodom and Gomorrah.

3.1.5 Health and pollution in Agbogbloshie

Public health concerns associated with e-waste recycling and disposal in the AEPS have received a lot of attention both locally and internationally. Procedures adopted by e-waste recyclers present significant threats to human health and contamination by hazardous chemicals to soil, water and air. The release of poisonous or hazardous chemicals such as lead, arsenic, mercury, dioxins, furans and brominated flame retardants during the crude and rudimentary processing of e-waste are often inhaled by workers or deposited on foodstuff and other edibles in the market. Exposure to these hazardous chemicals has been shown to be harmful both to children and adults, with children being the most vulnerable to the risk (Atiemo et al. 2012; Leung et al. 2006). Levels of these contaminants higher than the minimum or accepted limit in children could inhibit the development of the reproductive and nervous systems and also the brain thereby impacting on the IQ.

3.1.6 History of Agbogbloshie

According to Amoyaw-Osei et al. (2011) the establishment of the Agbogbloshie was driven by spill-over population associated with the exodus from the north of Ghana as a result of tribal conflicts, social downward movement by people forced out of more prime areas in the national capital, Accra. Though started as a foodstuff market for onions and yam, Agbogbloshie has over the years grown into a slum with residents and workers dealing in all kinds of activities. Agbogbloshie is well known as disposal site for old electrical and electronic products and household waste. Tons of e-waste end up Agbogbloshie on daily basis, where they are dismantled to extract copper and other valuable fractions. The custodians of the land, National Youth Council (NYC), permitted the scrap dealers started to erect temporary structures to house their wares and activities and in 1994 registered with the NYC as the Scrap Dealers' Association of Ghana. The location, now known as the Agbogbloshie e-waste processing site (AEPS) has become the main hub of the informal e-waste recycling industry in Ghana.

3.2 Materials

The materials used to examine e-waste governance and management as well as to assess the impacts of e-waste activities of the informal recyclers in Ghana are discussed in the following subsections.

3.2.1 Data used

In order to examine factors affecting e-waste management and governance efficiency, assess the impacts and identify options to formalize the informal e-waste sector, the data as listed in Table 3.1 was used.

Table 3.1: Data used

Data	Source
The Basel Convention on trans-boundary movement of hazardous waste and it disposal	Basel Secretariat
The Bamako Convention on trans-boundary movement of hazardous waste and its disposal in Africa	Africa Union
The 1994 Environmental Protection Agency Act	EPA, Accra
The prohibition of used refrigerators	Energy Commission, Ghana
The ban on export of scrap metals	Ministry of Trade, Ghana
The hazardous and e-waste management bill (Draft)	EPA, Ghana
Questionnaires and interviews (Appendix 1)	
Dutch Environmental Ministry; soil quality standards	Netherlands, EPA
Canadian Environmental Ministry; soil quality standards	Canadian EPA
Proceeding of the e-waste management conference in Ghana, 2011	StEP Initiative, Bonn
The informal economy: enabling transition to formalization	ILO, Geneva
Modernizing the informal sector	UN, Department of Economic and Social Affairs

3.2.2 Equipment used

The following equipment was used during this research (Table 3.2).

Table 3.2: Equipment used

Equipment	Use
GPS	For recording the coordinates of the collected soil samples
X-Ray fluorescence	To perform the elemental analysis for heavy metals from the soil samples collected
Reactor	To analyze rare earth metals in the soil samples
Soil auger (50 cm)	For collecting soil samples at the depth of 50 cm

3.2.3 Software used

Data preparation and arrangement was done using Microsoft Excel. Exploratory statistical analysis was done using Stata 13 and R 3.1.2 statistical software while geostatistical and spatial analysis was performed using ArcGIS 10.1. NodeXL was also utilized in mapping the stakeholders in the e-waste chain.

3.3 Methods

3.3.1 Determination of factors affecting the management and governance of e-waste in Ghana

With the aim to provide knowledge on the factors affecting the management and governance of e-waste in Ghana, interviews, observations and a desktop review of relevant documents and literature were conducted. Qualitative methods in the form of interviews using open-end as well as structured questionnaires (Appendix 1), observations and personal interaction were used. Twenty people comprising association leaders, members and workers at the AEPS were interviewed. The purposive sampling technique was used in the selection of the interviewees. The choice of this sampling technique was to ensure that the individual could provide first-hand information on the management and governance of e-waste within the informal sector.

Key representatives from the EPA and Country and City Waste Ltd (from the formal sector of e-waste management) were interviewed to learn their perspective on factors affecting the efficient management of e-waste in Ghana. Further, observations were made during field visits to follow the chain of e-waste management activities.

3.3.2 Assessment of impacts of e-waste in Ghana

Soil sampling

Soil sampling was done over the entire AEPS and its surroundings, i.e. within the AEPS areas for dismantling, burning, resting and recreation, and bordering areas such as residential, banks, police station, food market, eating places and worship areas. A total of 132 samples was collected from the area using a grid at 100-m intervals and purposive sampling procedure.

Sampling preparation and laboratory analysis

The samples were air dried at room temperature, sieved using a 100µm mesh, and pulverized into a 2.5 cm diameter thick pellet which was compressed using a 10-ton hydraulic press. Using acid tone, the equipment was cleaned after each procedure to avoid cross contamination. The heavy metal concentrations in the samples were analyzed using the x-ray fluorescence (XRF) spectrometer at a maximum power of 3000W (60Kv and 50mA). The pelleted samples were placed on a disk and then on the excitation source of the XRF for a 10 minute irradiation using silicon lithium Si(Li) detector with a resolution of 16V with Mn and Kα peak. To validate procedure and ensure quality control, the International Atomic Energy Agency (IAEA) Standard Reference IAEA Soil 7 was irradiated five times and average values compared with recommended values before analysis of the prepared samples.

Statistical and geostatistical analysis

The study adopted the steps as depicted in Figure 3.2 in the statistical and geostatistical analysis of the heavy metals Ba, Cd, Cr, Co, Cu, Hg, Pb and Zn identified in the soil samples.

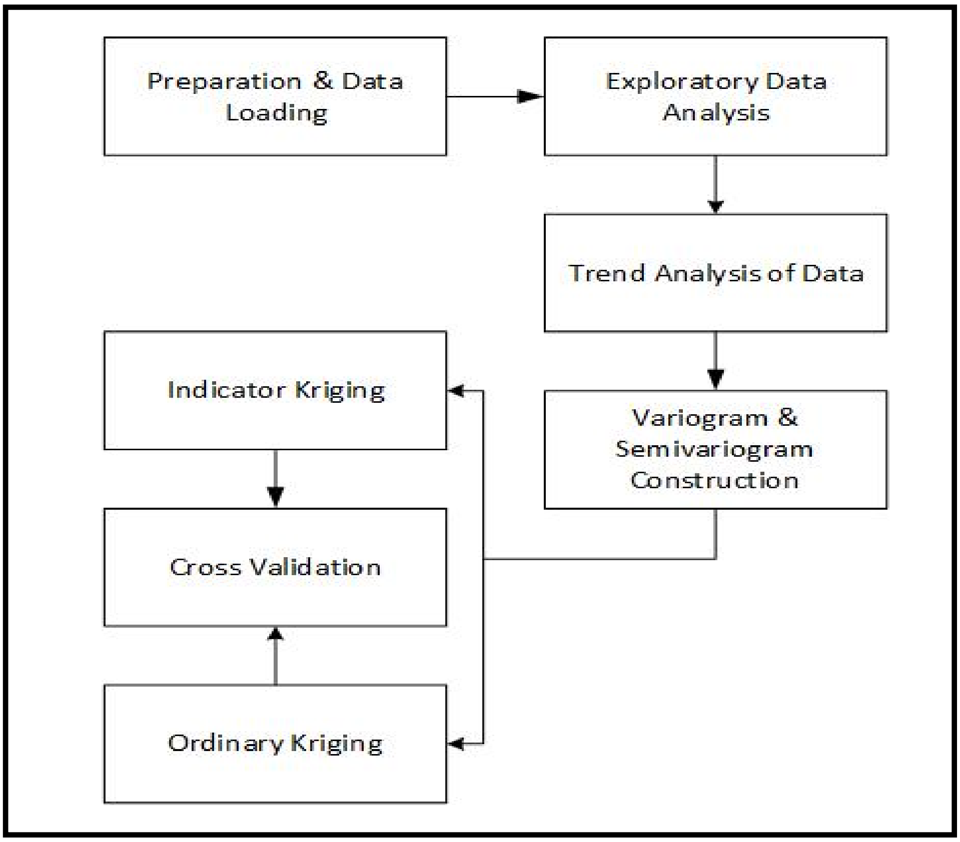

Figure 3.2: Statistical and geostatistical analysis

Data preparation and exploratory analysis

The heavy metal concentrations values together with the coordinates were prepared and arranged in Microsoft Excel and then loaded into R statistical software for the exploratory analysis. The descriptive variables assessed included the mean, median, minimum, maximum, standard deviation and skewness of the heavy metal concentrations. The heavy metal concentration variables were also analyzed for normality.

Analysis of trend and variogram construction

The trend analysis was performed to look for global trends or patterns in the data, which have to be taken into account before applying geostatistical interpolation. Variogram models were constructed for each heavy metal to examine the spatial autocorrelation of the variable; this defines the variability of the variable with itself through space. The Global Moran Index was also used to examine spatial autocorrelation. Spatial variability of the data was also assessed for each heavy metal using entropy voronoi maps before the kriging of the data (Cahn *et al*. 1994; Kerry and Oliver 2004). Exponential, spherical and K-Bessel models were chosen as they gave the best fit in the assessment of spatial autocorrelation for the heavy metal variables.

Kriging and cross validation

The final step in the geostatistical analysis was kriging of the data. As the data did not indicate any direction or local drift or trend, anisotropic kriging, universal kriging and co-kriging procedures were not used in the prediction. The ordinary kriging process was based on the calculation of the kriging estimation (distribution of heavy metals and potential ecological risk maps) by specifying the sill, nugget and range for each (exponential, K-Bessel and spherical) to interpolate the levels of the heavy metals at the unsampled locations.

Contamination and ecological risk assessment

The assessment of contamination was conducted based on the contamination factor and the degree of contamination as described under section 2.5.1. The estimation of the contamination factor in this study was based on Equation 2.5 and that of the degree of contamination, which is the sum of all contamination factors at a location, (Equation 2.6). In addition, the ecological risk assessment based on ecological risk factors (Equation 2.7) was conducted and potential ecological risk index (Equation 2.8) determined.

Exposure to heavy metals and health risk assessment

The human health risk was assessed as a measure of exposure of a person, and in this case children, to heavy metals. The USEPA (1996) model developed for human health risk was adopted in this study. In this study, the assessment was done based on the three pathways of exposure inhalation, dermal contact and by ingestion (Equations 2.9, 2.10 and 2.11, respectively; section 2.5.2). The human health risk due to exposure to heavy metals was estimated (Equation 2.13), while this was dependent on the hazard quotient determined in Equation 2.12. The health risk assessment in this study was estimated per the clusters within the AEPS.

Geo-accumulation index and rare earth metal assessment

The geo-accumulation index proposed by Muller (1969) was used in the assessment of possible rare earth metal resources that are lost due to the primitive methods of recycling by informal recyclers within the AEPS (Equation 2.4; section 2.5.1).

3.3.3 Formulating a framework to integrate the formal and informal sectors in managing e-waste in Ghana

The formulation of a framework to integrate the formal and informal e-waste management in Ghana was based on observations during fieldwork, interviews, questionnaires and a review of previous work done in the field of formalizing an informal sector.

Observations, interviews and questionnaires

Activities along the e-waste chain during field visits were followed, observed and documented. This phase of the research was used to identify stakeholders in the management and examine the social networks among the stakeholders. Personal interviews of key informants and questionnaires for collectors, recyclers and other downstream players were also administered (Appendix 1). The saturation sampling technique was used in administering the questionnaires, as the study related to this objective and network analysis was small and allowed detailed and complete analyses of each network location (Lin 1999).

Review of literature and secondary data

Reports including proceedings of the e-waste managers' conference in Ghana, and reports on formalization of informal sector by the United Nations and the International Labor Organization (Table 3.1). Secondary data vital for the formulation of a framework to integrate informal stakeholders were also sourced and obtained from these reports. Figure 3.3 gives an overview of steps used in formalizing the informal e-waste sector.

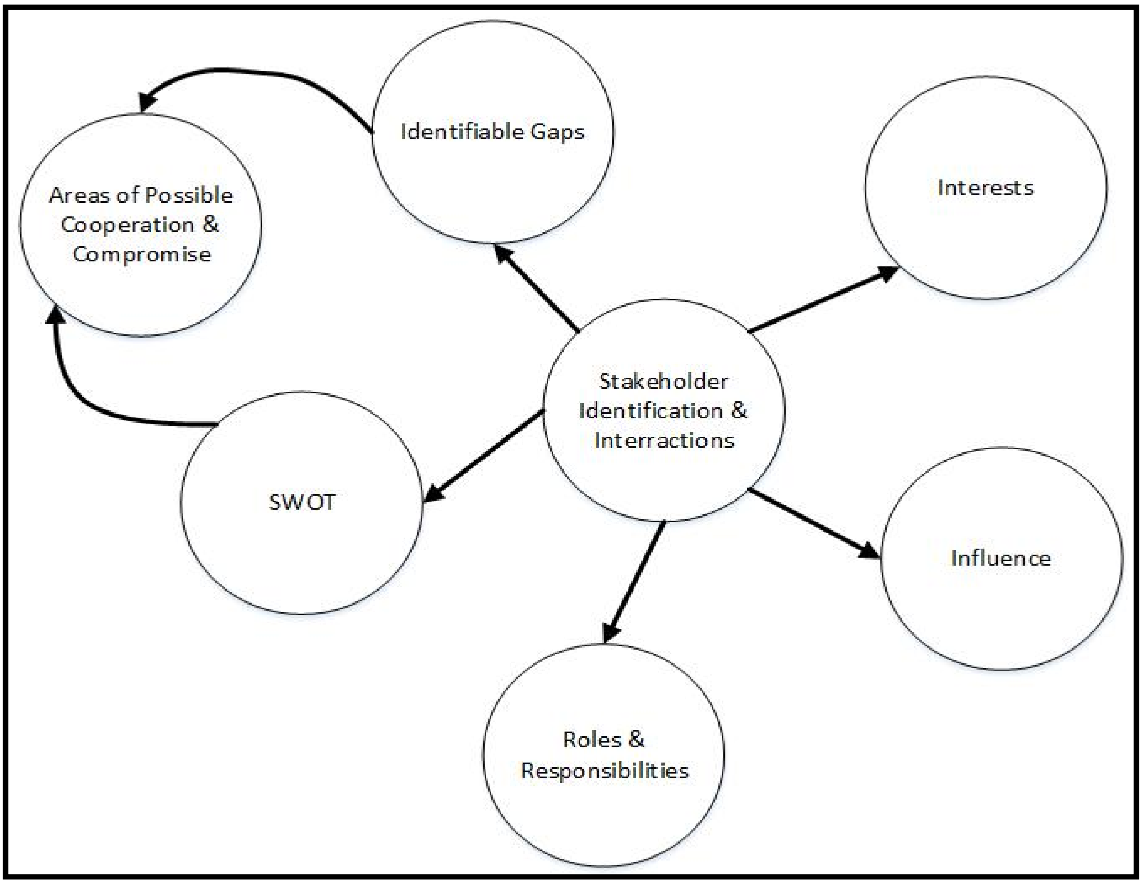

Figure 3.3: Steps in formalizing the informal sector

4 RESULTS AND DISCUSSION

4.1 E-waste management and governance structure in Ghana

Figure 4.1 gives a schematic diagram of the current e-waste governance and management structure in Ghana with agencies involved in the regulation and management of e-waste. Some stakeholders are involved along the entire chain of the e-waste sector (Figure 4.10, Table 7.1; Appendix 2a and 2b). The structure shows an uncoordinated set of institutions, agencies and regulations that are supposed to be used to monitor and manage the flow of activities by producers, importers, consumers, collectors, recyclers up to the final disposal of e-waste.

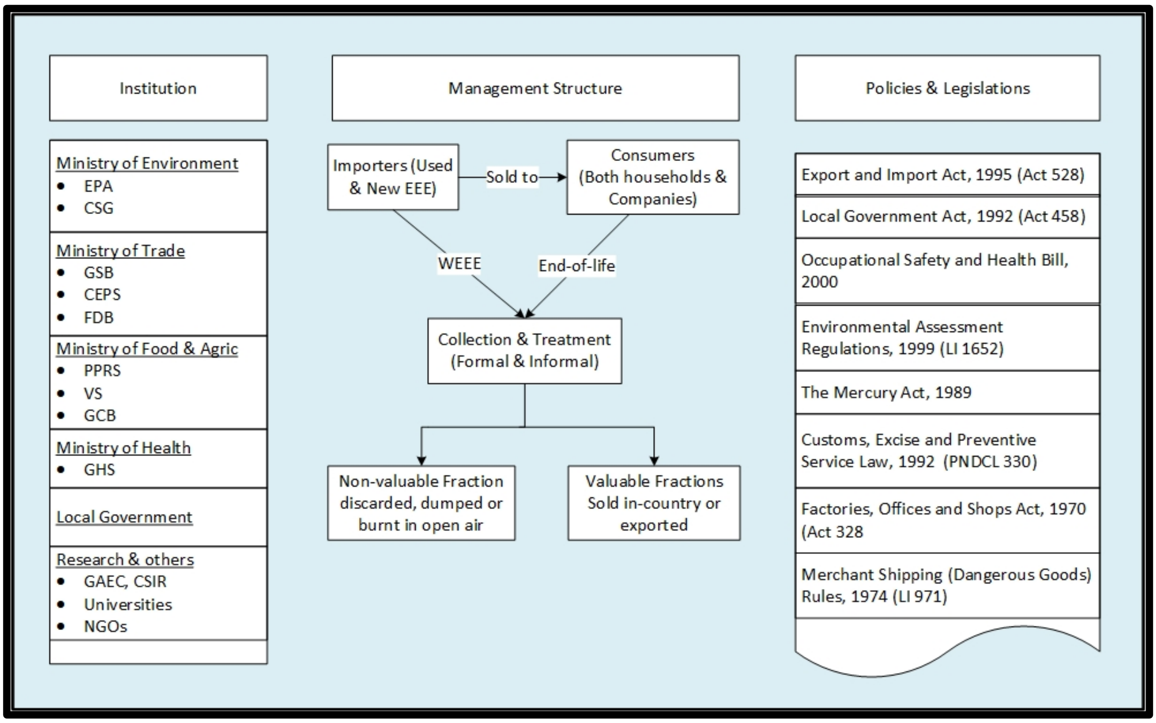

Figure 4.1: E-waste management structure in Ghana

4.2 Factors affecting e-waste management and governance

4.2.1 Lack of e-waste-specific legislation and enforcement

Although, related international and national e-waste legislation exist, the review of reports and documents (Table 3.1) revealed that there is no e-waste-specific legislation in Ghana. Ghana's ratification and signatory to international e-waste legislation, e.g. the Basel and the Bamako Conventions, has so far not been translated into country-specific e-waste legislation. It was widely perceived by respondents that this is the main reason for the almost out-of-control e-waste situation that exists in Ghana today. This situation is confirmed by Nnorom and Osibanjo (2008) and Sinha-Khetriwal et al. (2006) who state that the ineffective e-waste management in most developing countries stems from the fact that most of these countries lack country-specific e-waste legislation. This, together with the ambiguity in the e-waste legislation, makes the adherence to the current procedures (clearance including permitting and licensing, banning and awareness creation) meant to regulate e-waste management more difficult. Although aimed at filtering the amounts and kinds of EEE, the clearance system of permitting and licensing in addition to the collaborative efforts from the EPA, CEPS, GHPA and the VROMInspectorate (IV) to improve and facilitate enforcement and compliance so as to prevent harmful import and dumping of e-waste have shown to be inefficient. Furthermore, there is a paucity of qualified personnel to implement the existing legislation.

On the other hand, implementation and enforcement of e-waste legislation in developed countries have played an important role in curbing the occupational and environmental threats posed by these waste streams. Of concern to managers and environmental regulators of e-waste are the enforcement of signed and ratified international legislation, which seems not be enforced by both originating and receiving countries of these waste streams.

4.2.2 Inadequate management infrastructure and finance

Beside the lack of legislation and policy direction in the governance and management of e-waste in Ghana, inadequate infrastructure and finance to handle and manage e-waste is another critical issue. According to the EPA, personal communication with scientists in the field of e-waste and field observations, the lack or inadequate management infrastructure coupled with non-existence of e-waste-specific legislation and non-enforcement of e-waste related legislation in Ghana have contributed to the dominance of the informal sector and the crude recycling procedures adopted by the recyclers in the handling and disposal of e-waste.

In addition to the inadequate management infrastructure, there is a lack of financing mechanisms and investments in the sector. In contrast, in developed countries, producers and users of EEE share the responsibility of end-of-life management of such equipment through take-back schemes and extended producer responsibilities. These provide the necessary financing and investments in the e-waste management industry there (Widmer *et al*. 2005; Khetriwal *et al*. 2009). This is, however, not the situation in Ghana and the lack of producer responsibilities in Ghana adds to the inadequate financing and investment constraints in the management of e-waste.

4.2.3 Skills and technical capacity of managers

Field observations and the review of reports indicate that the e-waste sector in Ghana is largely dominated by poorly skilled informal sector players using simple technologies or crude recycling methods including open burning and wet leaching of chemicals in soil, surface and groundwater resulting in risks to human health and the environment. The lack of technologies and skills put limitations on e-waste processing and recycling, as policies and laws promulgated relative to the societal capability. According to the EPA, the lack of technological capacity is associated not only to just the informal recyclers but also to the entire e-waste chain (Pwamang 2009). The EPA also indicated that the lack of technology and capacity of qualified staff at the entry points means that some of the e-waste passes through these points undetected and hence increases the amount of e-waste coming into Ghana. The EPA further argues that, considering the human resource quality and strength, monitoring and regulatory agencies in Ghana are burdened by the volumes of equipment that they need to assess and examine before clearance is given.

4.2.4 Lack of institutional framework

With the institutional framework for the control and management of WEEE in Ghana provided for by Section 10 of the Environmental Protection Agency Act, 1994 (Act 490), there are several agencies involved along the entire chain of the e-waste sector (Figure 4.1). There is, however, a lack of a functional institutional framework or body responsible for the management of electronic waste in Ghana. The lack of clearly defined roles of the agencies breeds conflicts, and although the EPA is supposed to collaborate with a number of institutions in the disposal of unwanted materials there seems to be no single agency designated to coordinate their activities. This leads to lack of coordination among the relevant agencies, duplication of roles, and waste of resources. Lack of legislation, inadequate financing and limited skills combined with the lack of institutional framework is largely contributing to the management of e-waste in Ghana.

4.2.5 Awareness and public education

Effective management of electronic waste requires the cooperation of the general public, and as such the lack of comprehensive awareness on e-waste management on the part of consumers, collectors and recyclers, presents another barrier in the management of e-waste in Ghana. The lack of public awareness on the need for an e-waste management system, dangers of improper handling, and undefined roles of consumer and recyclers of e-waste contributes to the improper handling of e-waste. According to Kurian (2007), inadequate environmental awareness on the part of consumers and recyclers contributes to the country's difficulty in managing this waste stream. In addition, the unhealthy conditions of informal recycling is also attributed in part to lack of awareness of the dangers involved in the handling and disposal of e-waste (ATE 2012). Furthermore, there is a lack of safety standards in handling and managing of e-waste at the various recycling and processing sites.

4.3 Environmental impacts from e-waste processing

4.3.1 Descriptive statistics

The kurtosis and skewness values for Co, Cd, Cr and Hg were relatively low (Table 4.1). However, values for Ba, Pb, Zn, Cu and Ni were high, which indicates non-normality of the dataset for these heavy metals. The significant differences between the mean and the median of all heavy metals also prove that the datasets were not normally distributed. Furthermore, the coefficients of variation (CV) of Ni, Pb, Cu and Zn were 6.05, 1.82, 1.81 and 1.40, respectively, and higher than those of Ba, Co, Cr, Cd and Hg, suggesting that the former had greater variation among the soils in the study area.

Table 4.1. Summary statistics of heavy metal concentrations (ppm) in soil

Heavy Metal	Mean	Median	Min	Max	Stdv	CV	Skewness	Dutch SQGV		Canadian SQGV
								Optimal	Action	
Ba	627.66	574.03	120.60	2635.00	339.05	0.54	1.88	200	625	500
Cd	6.56	3.85	0.40	26.50	6.84	1.04	1.35	1	12	10
Co	46.64	35.25	8.80	153.70	29.17	0.63	1.12	20	240	–
Cr	296.60	197.30	21.10	1332.00	273.26	0.92	1.57	100	380	64
Cu	1387.96	290.65	9.40	18285.00	2507.19	1.81	3.70	36	190	63
Hg	2.70	1.40	0.40	13.40	2.89	1.07	2.03	0	10	7
Ni	61.68	13.95	0.60	4003.00	373.36	6.05	10.59	35	210	50
Pb	953.21	290.95	14.20	10280.00	1734.84	1.82	3.29	85	530	140
Zn	1371.14	576.55	41.90	12907.50	1923.75	1.40	3.07	140	720	200

Based on the Dutch and the Canadian environmental quality standard for soils, the mean values of the heavy metal concentrations of Ba, Cu, Pb and Zn were above both the optimal and action values of the Dutch and Canadian soil quality and guidance values (SQGV), while those of Cd, Co, Hg and Ni were below the action-required values. It is also worth indicating that all heavy metals apart from Co showed maximum concentrations significantly above the action-required values.

Transformation and normality of data

As the heavy metals were not normally distributed, the datasets were log transformed (Table 4.2). The kurtosis and skewness values for all the heavy metals then decreased. The closeness of the mean and median values for all heavy metals under study also indicates normality of the dataset after transformation. The coefficient of variation of all heavy metals apart from Hg also decreased. The previously high coefficient of variation for Ni, Pb, Cu and Zn reduced to 0.53, 0.25, 0.29 and 0.19, respectively; the coefficient however of Hg increased to 1.55 after transformation.

Table 4.2: Summary statistics of log-transformed heavy metal datasets

Heavy Metal	Mean	Median	Min	Max	Stdv	CV	Skewness	Kurtosis
LnBa	6.31	6.35	4.79	7.88	0.53	0.08	-0.29	0.17
LnCd	1.26	1.35	-0.92	3.28	1.21	0.96	-0.13	-1.17
LnCo	3.66	3.56	2.17	5.04	0.62	0.17	0.01	-0.73
LnCr	5.30	5.28	3.05	7.19	0.91	0.17	0.04	-0.80
LnCu	5.95	5.66	2.24	9.81	1.70	0.29	0.19	-1.06
LnHg	0.57	0.34	-0.92	2.60	0.88	1.55	0.59	-0.56
LnNi	2.68	2.64	-0.51	8.29	1.41	0.53	0.11	1.10
LnPb	5.80	5.67	2.65	9.24	1.46	0.25	0.32	-0.68
LnZn	6.50	6.36	3.74	9.47	1.22	0.19	0.18	-0.68

Relationships between heavy metals in soil

Using the Pearson product moment correlation matrix, the correlations between the heavy metals under study were conducted (Table 4.3). These indicate significant correlation at $p<0.05$ of Ba with all heavy metals apart from Ni and Pb. Cd also showed significant correlation with all other heavy metals apart from Cr and Ni, while Co also showed significant correlation at $p<0.05$ with Cr, Cu, Hg and Zn but was weakly correlated with Ni and Pb. Ni only correlated significantly with Hg but weakly with all other heavy metals.

Table 4.3: Correlation between heavy metals in soil

Heavy Metal	Ba	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
Ba	1								
Cd	0.712*	1							
Co	0.748*	0.599*	1						
Cr	0.604*	0.356	0.549*	1					
Cu	0.449*	0.761*	0.435*	0.042	1				
Hg	0.602*	0.804*	0.563*	0.19	0.855*	1			
Ni	0.115	0.050	0.328	0.001	0.181	0.472*	1		
Pb	0.341	0.724*	0.266	-0.139	0.903*	0.874*	0.250	1	
Zn	0.549*	0.767*	0.598*	0.252	0.856*	0.778*	0.140	0.775*	1

*Significant at $p < 0.05$

The transformed data, however, showed improved correlation among the heavy metals (Table 4.4). Values still indicate a weak correlation of Cr with Cd, Cu, Hg, Pb and Zn, while Ni, which previously did not correlate significantly with the other heavy metals apart from Hg after transformation, correlated significantly with all the heavy metals.

Table 4.4: Correlation between heavy metals after transformation

Heavy Metal	LnBa	LnCd	LnCo	LnCr	LnCu	LnHg	LnNi	LnPb	LnZn
LnBa	1								
LnCd	0.587	1							
LnCo	0.694	0.664	1						
LnCr	0.496	0.119**	0.526	1					
LnCu	0.571	0.916	0.694	0.080**	1				
LnHg	0.612	0.786	0.574	0.148**	0.829	1			
LnNi	0.618	0.606	0.865	0.409	0.667	0.586	1		
LnPb	0.467	0.872	0.502	-0.083**	0.914	0.870	0.524	1	
LnZn	0.677	0.766	0.783	0.320**	0.843	0.697	0.690	0.713	1

** *Not significant at $p<0.05$*

The overall descriptive analysis of the datasets of Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn reveals that variation and concentrations were several magnitudes higher than the concentrations that require intervention. These reflect activities within the AEPS. The data also showed skewness towards the burning areas of the AEPS, which suggests activities in this area as a contributing factor of heavy metal concentration. The skewness could also reflect the influence of some highly contaminated soils in the AEPS. The results of the analysis are comparable with those in other related research on heavy metal from e-waste processing sites (Leung *et al*. 2008; Caravanos *et al*. 2011; Atiemo *et al*. 2012; Itai *et al*. 2014). The metals Ba, Cr, Cu, Ni, Pb and Zn studied for pollution or contamination assessment also confirms and conforms to other heavy metals that have been used in contamination assessments. The choice of these heavy metals is possibly due to their level of toxicity and the threat they pose to the environment and human health. The concentrations of Cd, Co and Hg above the limit of both Dutch and Canadian standards also suggest that recyclers possibly recycle all kinds of e-waste, as these metals are more inherent in equipment such as television sets, batteries and transistors.

4.3.2 Geostatistical analysis of heavy metals

The occurrence of exceptional values can lead to data discontinuity, which would violate the geostatistics theory. In this study, data outside of the extent of A±3s were considered as exceptional values, where *A* denotes the average value for each heavy metal, and *s* is the standard deviation. Only data exceeding the value A+3s were found in the raw datasets and were replaced with the maximum value of data set without exceptional values to ensure spatially continuous data. The datasets were then analyzed for spatial autocorrelation using the global Moran index (Table 4.5) based on the null hypothesis that there is no spatial autocorrelation in the dataset. For geostatistical prediction and the methods of kriging, spatial autocorrelation must be present.

Table 4.5: Global Moran index parameters for spatial autocorrelation

Heavy Metals	Parameters of Spatial Autocorrelation					
	Moran index	**Expected Value**	**Variance**	**Z-Score**	**p-value**	**Distance Threshold (m)**
Ba	0.174	-0.008	0.006	2.321	0.020	500
Cd	0.124	-0.011	0.012	1.223	0.221	500
Co	0.07	-0.008	0.006	0.989	0.364	500
Cr	0.251	-0.008	0.006	3.317	0.001	500
Cu	0.144	-0.008	0.006	1.963	0.049	500
Hg	0.175	-0.014	0.043	0.918	0.358	250
Ni	0.064	-0.009	0.019	0.528	0.598	250
Pb	0.173	-0.008	0.006	2.364	0.018	500
Zn	0.165	-0.008	0.006	2.223	0.026	500

The results of the spatial autocorrelation indicate Ba, Cr, Cu, Pb and Zn as having Z-score values above the threshold value of 1.6 and associated $p<0.05$ to indicate significance at distance values of 500 m. This implies that the length of the spatial autocorrelation is much longer than the sampling interval of 100 m and also rejection of the null hypothesis for Ba, Cr, Cu, Pb and Zn. Thus, these metals are spatially autocorrelated. The Z-score values, however, for Cd, Co, Hg and Ni, which were 1.223, 0.989, 0.918 and 0.528, respectively and lower than the Z-score threshold value at $p>0.05$, revealed no spatial autocorrelation.

Variation and spatial structure of heavy metals

The developed entropy voronoi maps show the variations in the data with respect to location and distance between the data points (Figure 4.2). The voronoi maps also give information on the stationarity of the data, which is also a requirement before performing geostatistical prediction. The dark and light green areas show little variation in data, while those in orange and red show greater variation between neighboring areas, which implies that the latter areas have very different concentrations of heavy metals. All heavy metals showed relative stationarity, i.e., the spatial relationship between pairs of points is roughly the same across the study area. The spatial structure revealed by the sill, nugget, range and models that gave best fit of the semivariogram model are shown in Table 4.6.

Table 4.6: Spatial structure characteristics for the heavy metals

Heavy Metal	**Model**	**Nugget, C_o**	**Sill, C_1**	**C_o/C_1**	**Range**
Ba	Exponential	0.2781	0.8099	0.3434	888.74
Cr	Spherical	0.3673	0.8410	0.4367	1068.25
Cu	Exponential	0.2162	0.8725	0.2478	1057.40
Pb	Spherical	0.2260	0.8970	0.2519	1068.25
Zn	Spherical	0.2444	0.9725	0.2513	874.05

Figure 4.2: Entropy voronoi maps of heavy metals at AEPS

The ratio of nugget to sill is commonly used to express the spatial dependency of the heavy metals, and also indicates the predominant factors among all natural and anthropogenic factors (Robertson *et al.* 1997; Shi *et al.* 2008). A nugget to sill ratio less than 0.25 implies that the heavy metals in the dataset have a strong spatial dependency at the regional scale; a ratio between 0.25 and 0.75 indicates moderate spatial dependency, and a ratio greater than 0.75 a weak spatial dependency. This indicates that the Cu showed a strong spatial dependency while Ba, Cr, Pb and Zn showed a moderate spatial dependency (Table 4.6). It can thus be assumed that Cu in the soil is strongly associated with human activities. The metals Ba, Cr, Pb and Zn show moderate spatial dependency indicating they are affected by anthropogenic and natural factors.

Although, all datasets revealed stationarity or spatial variation through the entropy voronoi maps (Figure 4.2) only five (Ba, Cr, Cu, Pb and Zn) out of the nine heavy metals showed spatial autocorrelation increasing in the order of autocorrelation from Cu, Zn, Ba, Pb to Cr. The presence of spatial autocorrelation gives a possible indication of spatial random variance, and hence a further indication of the artificial nature of these heavy metals in the soil samples. This also suggests anthropogenic input as a significant source of these heavy metals.

4.3.3 Contamination assessment

Contamination factor

Table 4.7 shows summary statistics on the calculation of contamination factor with the detailed location by location contamination factors provided in Appendix 4. According to the Hakanson (1980) classification (Table 2.5) mean contamination factors of Ba, Co, Cr and Ni were 1.46, 1.86, 2.94 and 0.37, respectively, and thus indicate moderate contamination. The mean contamination factors of Cd, Cu, Hg, Pb and Zn were approximately 5, 4, 5, 11 and 3 times, respectively, above the lower limit of the high contamination factor. Zn, Cu and Pb showed the highest coefficient of variation in the order 1.15, 1.53 and 1.62, respectively, while Cd, Ni, Hg, Cr, Co and Ba showed the lowest in the order 1.04, 1.01, 0.99, 0.90, 0.61 and 0.48, respectively.

Table 4.7: Summary statistics of contamination factors of heavy metals

Heavy Metal	Mean	Median	Stdv	Min	Max	C.V	Skewness	Kurtosis
Ba	1.46	1.35	0.70	0.28	3.46	0.48	0.66	-0.07
Cd	32.80	19.25	34.20	2.00	132.50	1.04	1.35	1.02
Co	1.86	1.41	1.14	0.35	5.16	0.61	0.99	0.21
Cr	2.94	1.98	2.64	0.21	10.99	0.90	1.40	1.24
Cu	23.11	5.28	35.33	0.17	150.07	1.53	2.20	4.56
Hg	32.61	17.50	32.43	5.00	123.75	0.99	1.63	1.70
Ni	0.37	0.19	0.37	0.01	1.41	1.01	1.18	0.55
Pb	70.25	23.28	113.67	1.14	472.24	1.62	2.63	6.39
Zn	17.85	8.24	20.51	0.60	77.11	1.15	1.60	1.76

Degree of contamination

To describe the extent of contamination and also to examine the toxicity of the metals under investigation, the degree of contamination (see Equation 2.6), which is calculated as the sum of all contamination factors for each element present at a site or location, was done (Table 4.8). Table 4.8 also shows spatial autocorrelation, and the nugget, sill and range of the degree of contamination.

Table 4.8: Statistics and geostatistical parameters, degree of contamination

Mean	Median	Stdv	Minimum	Maximum	CV	Skewness	Kurtosis
158.68	63.21	222.42	3.36	968.01	1.40	2.13	4.14

Spatial Autocorrelation

MI	E.V	Variance	Z-Score	P-Value	DT
0.175	-0.008	0.006	2.362	0.018	500

Geostatistical characteristics

Model	Nugget, C_o	Sill, C_1	C_o/C_1	Range
Spherical	0.2191	1.0220	0.2144	851.49
Exponential	0.2885	0.9114	0.3166	1057.4
Gaussian	0.3498	0.8979	0.3896	712.01
K-Bessel	0.3440	0.9163	0.3754	753.1

It can be observed that the mean degree of contamination of 156.68 was approximately five (5) times higher than the lower limit of the very high degree of contamination (Table 2.6), while the maximum value was approximately 30 times above that. The values also exhibited characteristics of spatial autocorrelation with a Z-score of 2.362 at a p-value of 0.018, which is above the 1.6 threshold global Moran index, which is the value for a dataset to attain spatial autocorrelation. It is an indication of human-induced activities influencing the degree of contamination. The spatial variation in the degree of contamination is depicted in the voronoi map as shown in Figure 4.2. Dark and light green areas indicate little variation while orange and dark red indicate greater variation. The map roughly indicates stationarity in the degree of contamination.

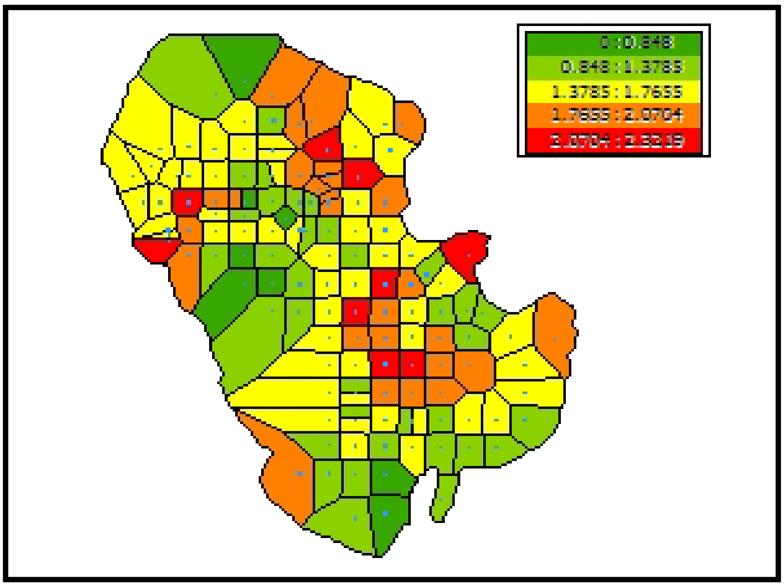

Figure 4.3: Voronoi map for degree of contamination in AEPS

Spatial structure of degree of contamination

The spatial structure and characteristics of the degree of contamination was further revealed by the variogram cloud and the surface, respectively (Figures 4.4 and 4.5). The cloud and surface showed the best correlation in northeast and southwest directions, indicating an omnidirectional orientation, and thus the data exhibited isotropy in the degree of contamination.

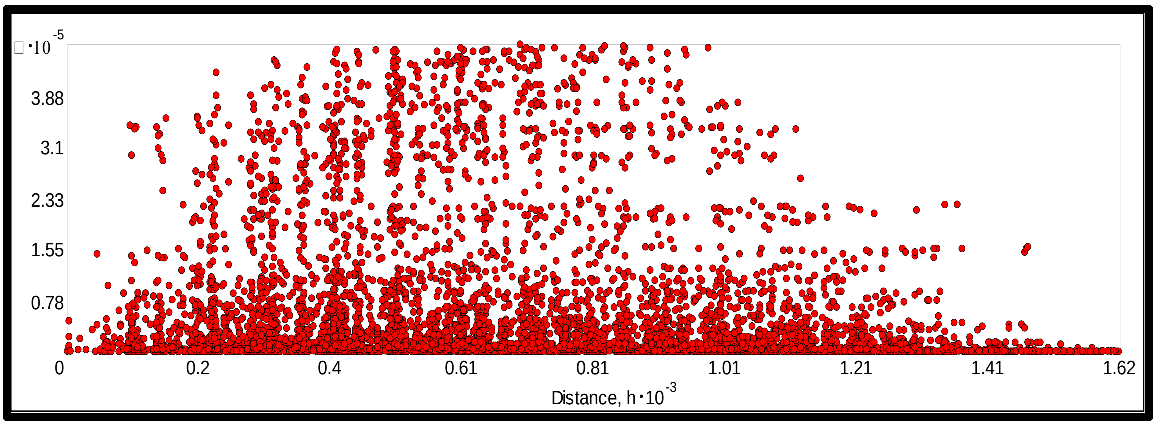

Figure 4.4: Semivariogram cloud for degree of contamination

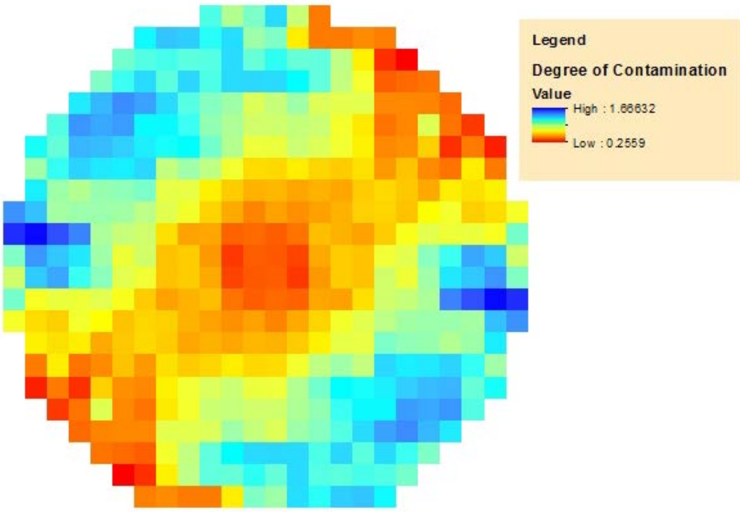

Figure 4.5: Semivariogram surface for degree of contamination

The isotropic semivariogram model for the degree of contamination exhibited a very good structure, which was best fitted with a spherical model in ArcGIS 10.1 (Figure 4.6). The model resulted in the following parameters: a nugget value of 0.2191, a sill of 1.0220 and a range of 851.49 m (Table 4.8). The nugget to sill ratio of the spherical model 0.2144 reveals that the sample density is adequate to reveal a good spatial structure and strong spatial dependence of the degree of contamination. Furthermore, a range of 851.49 also indicates that the length at which the data maintain spatial autocorrelation was longer than the general sampling interval of 100 m.

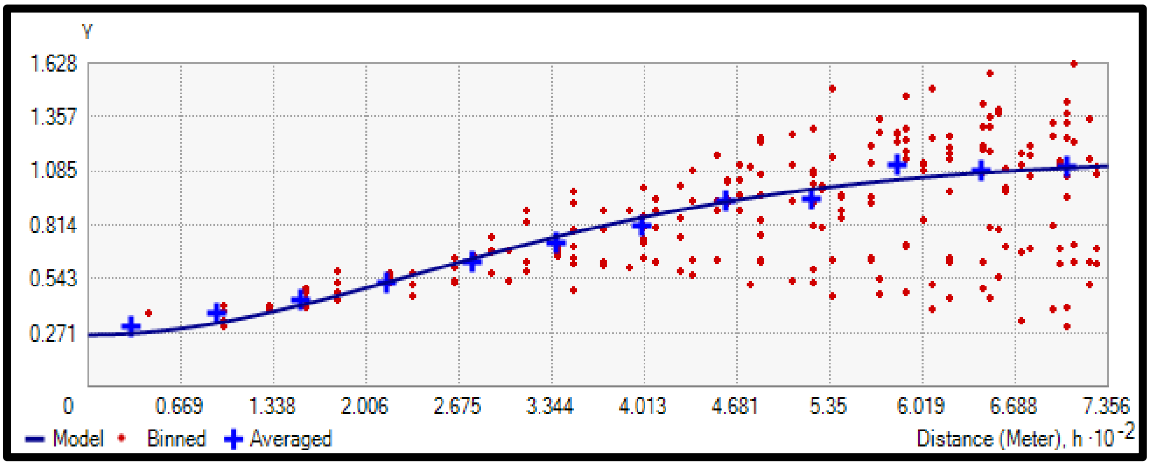

Figure 4.6: Isotropic semivariogram cloud fitted with spherical model

Spatial distribution map of degree of contamination

With the data on the degree of contamination exhibiting spatial autocorrelation being stationary, omnidirectional (isotropic) and showing moderate spatial dependency, simple kriging was used to interpolate the surface. Figure 4.6 shows the spatial distribution and extent to which the AEPS is contaminated. For the purpose of examining the degree of contamination, the kriged surface was reclassified according to the classification of degree of contamination by Hakanson (1980) (Table 2.5). A further assessment of the spatial distribution map revealed 66% representing 110ha of land area classified as very high contamination while 25% (42ha), 8% (14ha) and less than 1% classified as considerable, moderate and low degree of contamination respectively.

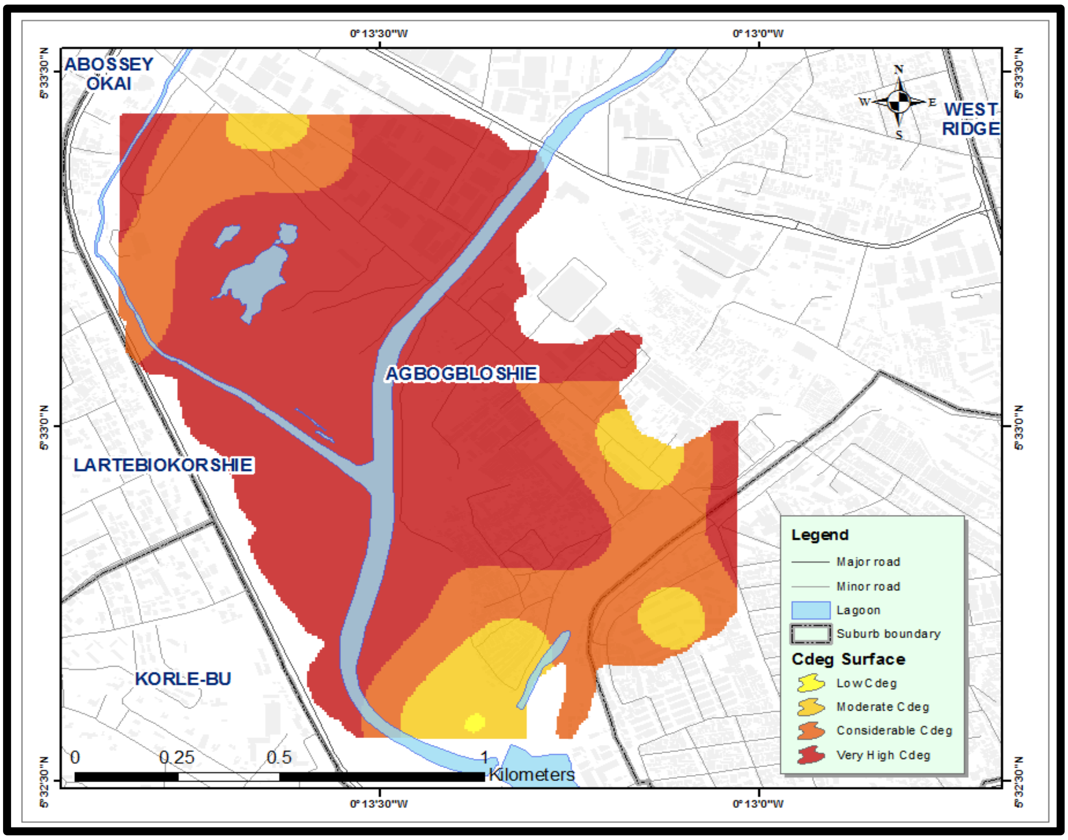

Figure 4.7: Spatial distribution map for degree of contamination (C_{deg})

The contamination factor shows the contribution of each of the heavy metals to the degree of contamination, and Zn, Cu, Hg, Cd and Pb in an increasing order as contributing immensely to the degree of contamination. The kriged map for the degree of contamination estimated on the basis of the contamination factor and reference values is similar to data used in studies by Muller (1969), Hakanson (1980), Lu et al. (2009) and Atiemo et al. (2012). The map shows that most of the areas within the AEPS were highly or severely contaminated with the studied heavy metals. The significantly high degree of contamination, exhibition of spatial autocorrelation, and spatial random variance in the degree of contamination points to the likely influence of anthropogenic input, i.e., through the activities of the e-waste recyclers. The school, residential, market, farm and worship areas are of particular concern as children are frequently present in these areas and heavy metals such as Pb and Cd are known to cross the blood brain barriers of children exerting toxic or hazardous effects causing low IQ, developmental disorders and cancer (Frazzoli *et al*. 2010; Atiemo *et al*. 2012; Riederer *et al*. 2013).

4.3.4 Ecological risk assessment

Ecological risk factors

For an area earmarked for an ecological restoration zone within Accra, the ecological risk factor for each heavy metal under investigation as well as the overall potential ecological risk were calculated using Equations 2.7 and 2.8. The purpose of the assessment is to provide an empirical basis for understanding the ecological risks associated with these heavy metal concentrations in the soils in the AEPS. The assessment was conducted based on six heavy metals where the toxicity response factor is provided by Hakanson (1980). Table 4.9 lists the summary statistics of the ecological risk factors with detailed potential ecological risk factor for each heavy metal given in Appendix 3.

Table 4.9: Summary statistics of ecological risk factors

Metal	Mean	Median	Stdv	Min	Max	CV	Skewness	Kurtosis
Cd	984.02	577.50	1026.14	60.00	3975.00	1.04	1.35	1.02
Cr	5.88	3.95	5.27	0.42	21.98	0.90	1.40	1.24
Cu	115.56	26.42	176.66	0.82	750.36	1.53	2.20	4.56
Hg	1304.58	700.00	1297.11	200.00	4950.00	0.99	1.63	1.70
Pb	351.24	116.38	568.33	5.68	2361.20	1.62	2.63	6.39
Zn	17.85	8.24	20.51	0.60	77.11	1.15	1.60	1.76

The mean and maximum Cr values show a “low ecological risk”, as the factors are all below 40. This also applies to the mean risk factor for Zn, however, the maximum value indicates moderate ecological risk. The mean and maximum ecological risks for Cd, Hg and Pb are significantly high with a value above 320. The order of the level of heavy metal toxicity is Hg>Cd>Pb>Cu>Zn>Cr, indicating that these metals will in this order contribute significantly to the potential ecological risk in the study area.

Spatial structure of potential ecological risk index (PERI)

Table 4.10 shows the summary statistics and geostatistical parameters of the ecological risk index. The significant difference between the mean and the median, and the skewness and kurtosis indicates that the ecological risk index is not normally distributed. The Gaussian Kernel normal score transformation shows that the ecological risk index dataset was spatially autocorrelated with a Moran index at a Z-score of 2.342 and p-value of 0.023 at a threshold distance of 500 m (Table 4.9). Of the four models used to test for the fit of the isotropic model of the potential ecological risk index, a strong spatial dependency in the order of Exponential>Spherical>K-Bessel>Gaussian was revealed by the nugget to sill ratio, as the smaller the ratio, the stronger the spatial dependency. The exponential model therefore gave the best fit of the isotropic semivariogram (Figure 4.8).

Table 4.10: Summary statistics and geostatistical parameters of PERI

Mean	**Median**	**Stdv**	**Min**	**Max**	**CV**	**Skewness**	**Kurtosis**
1892.67	694.57	2774.86	8.04	12122.46	1.46	2.01	3.47
Spatial autocorrelation							
MI	**EV**	**Variance**	**Z-score**	**P-value**	**DT**		
0.168	-0.008	0.006	2.2770	0.023	500		
Other geostatistical parameters							
Model	**Nugget,C_0**	**Sill, C_1**	**C_0/C_1**	**Range**			
Spherical	0.2035	0.8328	0.2444	719.47			
Exponential	0.1754	0.9202	0.1906	1099.54			
Gaussian	0.2787	0.6856	0.4065	495.46			
K-Bessel	0.2734	0.6995	0.3909	518.78			

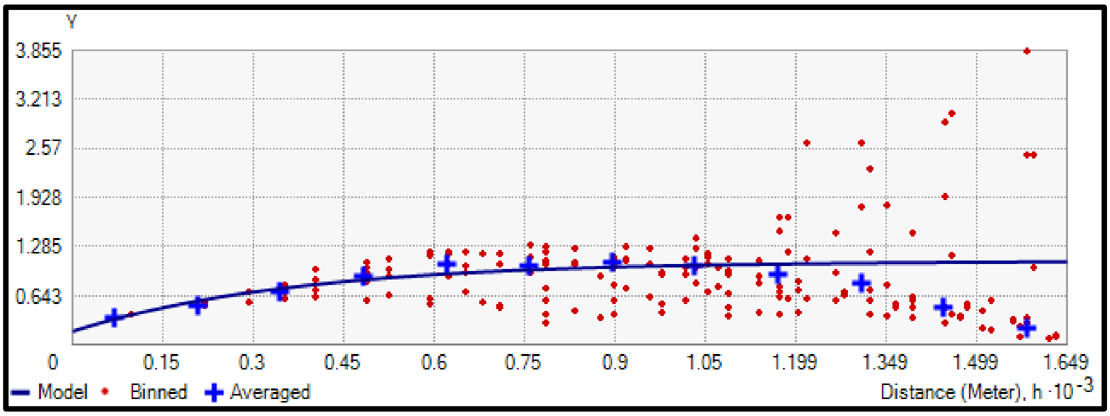

Figure 4.8: Isotropic semivariogram cloud fitted with exponential model for PERI

Spatial distribution of potential ecological risk index

Figure 4.9 shows the spatial distribution map of the potential ecological risk index within the AEPS. The map shows that areas of the burning and dismantling areas and some parts of the commercial areas as having a very high potential ecological risk index. The map also shows many more areas as being zones with potentially lower ecological risks although these areas had been predicted as contaminated (Figure 4.6). With parts of the very high potential ecological risk zones housing cattle rearing sites, livestock, farms (for vegetable production) and aquatic species in the nearby stream, these present current and future health risks. In general 59% (98 ha), 20% (33 ha), 8% (14 ha) and 13% (23 ha) of land areas in the AEPS respectively classified as significantly high, high, moderate and low potential ecological risk zones respectively.

The estimation of the potential ecological risks was conducted to evaluate the degree to which soil associated with chemical pollutants might impact on aquatic and terrestrial organisms including plants (Wenning and Ingersoll 2002; Bai et al. 2011). The ecological risk index for the AEPS also represents the sensitivity of biological communities to hazardous substances. The ecological risk indices of the AEPS account for the contamination caused by Cd, Cu, Hg, Pb and Zn, and indicate that the AEPS is considerably impacted by the contamination. Among the different areas within the AEPS, the indices show potentially high risks in the burning, dismantling, commercial, farms and areas close to water bodies and in some parts of the residential areas.

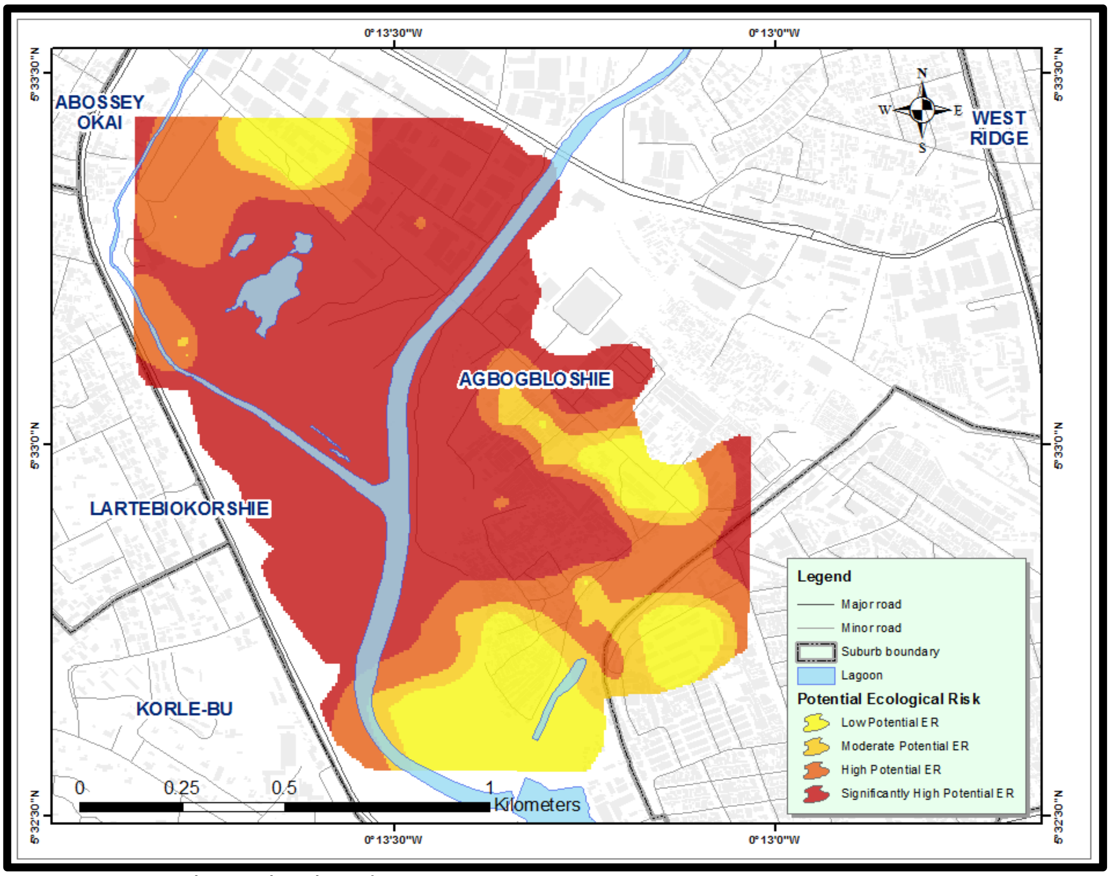

Figure 4.9: Ecological risk index map

Of particular concern are significantly high risk levels in the farm areas, which could negatively impact on plants as the detrimental effects of heavy metals in plants and the subsequent transfer to humans and other organisms can be expected. Also, areas close to water bodies are at high ecological risk as deposits of these contaminants can seep into these water bodies thus impacting on aquatic species. Similar heavy metal contaminations impacting on both terrestrial and aquatic species have been observed by Bryan (1971); Bryan and Gibbs (1983) as well as Dallinger *et al*. (1987). Organisms in the soil and plants or water bodies in the areas of the clinics, school, parts of the market area and some parts of the commercial areas face no ecological risks although the spatial distribution of the degree of contamination map (Figure 4.7) shows these areas as contaminated.

4.4 Health risk assessment of heavy metals

The highest mean concentration of the heavy metals alternated between the burning and dismantling sites (Table 4.11), which is not surprising as the main activities of e-waste processing take place there. Cd, Cu and Pb showed the highest mean concentrations in the burning sites, while Co, Cr, Ni and Zn showed the highest values in the dismantling sites. The highest Ba value was, however, found in the areas close to the worship area. Cd and Ni were not measured in samples collected from areas close to the clinics.

Table 4.11: Mean concentrations of heavy metal per site cluster

Site	Ba	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
Burning	641.51	10.10	43.81	171.53	2967.80	3.47	21.84	2666.38	1887.23
Commercial area	493.63	0.62	29.60	290.94	157.73	0.35	6.21	163.98	516.91
Clinics	581.10	_	28.45	119.25	40.70	_	_	55.75	220.50
Dismantling	785.67	7.81	66.12	419.20	1643.58	1.59	44.64	846.84	1939.22
Farm	315.42	0.18	23.74	319.22	91.42	0.50	4.88	143.50	271.22
Recreational	443.70	1.87	36.51	338.61	762.86	0.52	14.75	355.16	700.31
Residential	658.08	2.63	51.53	153.87	1354.60	1.64	27.19	896.06	1170.41
School	394.35	0.25	42.25	118.75	47.55	0.55	2.20	111.30	293.15
Worship	783.90	0.30	30.53	184.63	118.17	0.43	4.93	117.00	419.97

4.4.1 Exposure pathways of heavy metals

Tables 4.11, 4.12 and 4.13 provide the hazard quotients per exposure pathway of Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn. The exposure pathways are in the order inhalation<dermal contact<ingestion. For the ingestion pathway (Table 4.11), Cr, Pb and Ba (order Cr>Pb>Ba) were the three heavy metals with the highest hazard quotients, and a similar trend was also seen for the dermal pathway (Table 4.12). The heavy metal Cr showed the highest hazard quotient through inhalation, followed by Ba and Pb. It is also however worth noting that Ni and Zn had the lowest hazard quotient in all three exposure pathways.

Table 4.12: Hazard quotient for ingestion exposure pathway for heavy metals

Area	Hazard quotients (ingestion exposure pathways)								
	Ba	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**
Burning	6.03E-02	6.64E-02	1.44E-02	3.76E-01	4.88E-01	5.70E-02	7.18E-03	5.01E+00	4.14E-02
Commercial Area	4.64E-02	4.10E-03	9.73E-03	6.38E-01	2.59E-02	5.75E-03	2.04E-03	3.08E-01	1.13E-02
Clinics	5.46E-02	_	9.35E-03	2.61E-01	6.69E-03	_	_	1.05E-01	4.83E-03
Dismantling	7.38E-02	5.13E-02	2.17E-02	9.19E-01	2.70E-01	2.61E-02	1.47E-02	1.59E+00	4.25E-02
Farm	2.96E-02	1.18E-03	7.80E-03	7.00E-01	1.50E-02	8.22E-03	1.60E-03	2.70E-01	5.94E-03
Recreational	4.17E-02	1.23E-02	1.20E-02	7.42E-01	1.25E-01	8.51E-03	4.85E-03	6.67E-01	1.53E-02
Residential	6.18E-02	1.73E-02	1.69E-02	3.37E-01	2.23E-01	2.69E-02	8.94E-03	1.68E+00	2.57E-02
School	3.70E-02	1.64E-03	1.39E-02	2.60E-01	7.82E-03	9.04E-03	7.23E-04	2.09E-01	6.43E-03
Worship	7.36E-02	1.97E-03	1.00E-02	4.05E-01	1.94E-02	7.12E-03	1.62E-03	2.20E-01	9.20E-03

Table 4.13: Hazard quotient for dermal exposure pathway for heavy metal

Area	Hazard quotients (dermal exposure pathways)								
	Ba	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**
Burning	2.41E-03	1.86E-02	5.04E-05	5.26E-02	4.55E-03	3.04E-03	7.45E-05	9.35E-02	5.79E-04
Commercial Area	1.85E-03	1.15E-03	3.41E-05	8.93E-02	2.42E-04	3.07E-04	2.12E-05	5.75E-03	1.59E-04
Clinics	2.18E-03	_	3.27E-05	3.66E-02	6.24E-05	_	_	1.96E-03	6.77E-05
Dismantling	2.95E-03	1.44E-02	7.61E-05	1.29E-01	2.52E-03	1.39E-03	1.52E-04	2.97E-02	5.95E-04
Farm	1.19E-03	3.31E-04	2.73E-05	9.80E-02	1.40E-04	4.38E-04	1.66E-05	5.03E-03	8.32E-05
Recreational	1.67E-03	3.44E-03	4.20E-05	1.04E-01	1.17E-03	4.54E-04	5.03E-05	1.25E-02	2.15E-04
Residential	2.47E-03	4.83E-03	5.93E-05	4.72E-02	2.08E-03	1.44E-03	9.27E-05	3.14E-02	3.59E-04
School	1.48E-03	4.60E-04	4.86E-05	3.64E-02	7.30E-05	4.82E-04	7.50E-06	3.90E-03	9.00E-05
Worship	2.95E-03	5.52E-04	3.51E-05	5.67E-02	1.81E-04	3.80E-04	1.68E-05	4.10E-03	1.29E-04

Table 4.14: Hazard quotient for inhalation exposure pathway for heavy metal

Area	**Hazard quotients (inhalation exposure pathway)**								
	Ba	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**
Burning	8.24E-04	1.86E-04	1.41E-03	1.10E-03	4.54E-05	3.03E-05	7.43E-07	9.33E-04	5.78E-06
Commercial Area	6.34E-04	1.14E-05	9.52E-04	1.87E-03	2.41E-06	3.06E-06	2.11E-07	5.74E-05	1.58E-06
Clinic	7.47E-04	_	9.15E-04	7.66E-04	6.23E-07	_	_	1.95E-05	6.75E-07
Dismantling	1.01E-03	1.43E-04	2.13E-03	2.69E-03	2.52E-05	1.39E-05	1.52E-06	2.96E-04	5.94E-06
Farm	4.05E-04	3.31E-06	7.64E-04	2.05E-03	1.40E-06	4.37E-06	1.66E-07	5.02E-05	8.30E-07
Recreational	5.70E-04	3.44E-05	1.17E-03	2.18E-03	1.17E-05	4.53E-06	5.02E-07	1.24E-04	2.14E-06
Residential	8.45E-04	4.82E-05	1.66E-03	9.88E-04	2.07E-05	1.43E-05	9.25E-07	3.14E-04	3.58E-06
School	5.07E-04	4.59E-06	1.36E-03	7.63E-04	7.28E-07	4.81E-06	7.49E-08	3.89E-05	8.98E-07
Worship	1.01E-03	5.51E-06	9.82E-04	1.19E-03	1.81E-06	3.79E-06	1.68E-07	4.09E-05	1.29E-06

4.4.2 Non-carcinogenic health risk of heavy metals

The non-carcinogenic health hazard indices of Ba, Cd, Co, Cu, Hg, Ni and Zn for children under 6 years in all study areas within the AEPS were below the 1 reference limit of environmental and regulatory agencies below which hazards are considered acceptable for children. The value however of Cr in the dismantling site were above the regulatory limit of 1 and considered unacceptable by environmental managers.

Table 4.15: Non-carcinogenic hazard index for heavy metals in AEPS

Area	Ba	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn
Burning	0.063	0.085	0.016	0.430	0.492	1.323	0.007	5.104	0.042
Commercial Area	0.049	0.005	0.011	0.729	0.026	0.134	0.002	0.314	0.011
Clinic	0.058	_	0.01	0.299	0.007	_	_	0.107	0.005
Dismantling	0.078	0.066	0.024	1.050	0.273	0.605	0.150	1.621	0.043
Farm	0.081	0.002	0.009	0.800	0.015	0.191	0.002	0.275	0.006
Recreational	0.044	0.016	0.013	0.848	0.127	0.197	0.005	0.68	0.016
Residential	0.065	0.022	0.019	0.385	0.225	0.625	0.009	1.715	0.026
School	0.039	0.002	0.015	0.297	0.008	0.21	0.001	0.213	0.007
Worship	0.078	0.003	0.011	0.463	0.020	0.165	0.002	0.224	0.009

The indices for Pb in the areas of burning, dismantling and residential were above the reference limit of 1, and as such considered as unacceptable for children within these areas. In the case of the burning area, the non-carcinogenic hazard index for Pb was five times higher than the reference limit of 1. The high health hazard indices of Cr and Pb in the burning, dismantling and residential areas could be an indication that the activities there could be a contributing factor to the potential hazard posed by heavy metals.

4.4.3 Carcinogenic health risk of heavy metals

The carcinogenic risk was calculated based only on the risk through inhalation for four carcinogenic heavy metals (Cd, Co, Cr and Ni) using the model as expressed in Equation 2.14. The carcinogenic risk of these heavy metals due to activities within the AEPS is low, as it is below the threshold range of values 10^{-4} and 10^{-6}. The index of these metals is in the order Cr>Co> Cd>Ni with risk indices of Cd and Ni alternating depending on the site.

Table 4.16: Carcinogenic health risk of heavy metals

Area	Cd	Co	Cr	Ni
Burning	3.26E-09	2.2E-08	3.69E-07	9.41E-10
Commercial Area	2.01E-10	1.49E-08	6.26E-07	2.67E-10
Clinics	_	1.43E-08	2.57E-07	_
Dismantling	2.52E-09	3.32E-08	9.03E-07	1.92E-09
Farm	5.81E-11	1.19E-08	6.87E-07	2.1E-10
Recreational	6.04E-10	1.83E-08	7.29E-07	6.35E-10
Residential	8.48E-10	2.59E-08	3.31E-07	1.17E-09
School	8.07E-11	2.12E-08	2.56E-07	9.47E-11
Worship	9.69E-11	1.53E-08	3.98E-07	2.12E-10

The health impact assessment of e-waste recycling activities within the AEPS showed an overall health risk regarding both carcinogenic and non-carcinogenic effects of the heavy metals identified. With respect to the non-carcinogenic effect on children, the ingestion of particles (Table 4.11) from the AEPS appears to be the exposure route with the highest impact followed by dermal contact and inhalation (Table 4.12). A similar pattern was also observed by Ferreira-Baptista and De Miguel (2005); Lim et al. (2008); Khan et al. (2008) and Zheng et al. (2010) in their studies of exposure to heavy metals. The hazard quotients of non-carcinogenic risk due to inhalation of fine particles from the AEPS is 1 to 4 orders of magnitude lower than that of ingestion and dermal contact. This makes the exposure to heavy metals through inhalation less risky to health, as according to Zheng et al. (2010) inhalation of re-suspended particles through the mouth and nose is almost negligible compared with ingestion and dermal contact. Furthermore, the above regulatory limits of the non-carcinogenic hazard index of Cr and Hg at all sites apart from the clinics, and that of Cu and Pb in the burning, dismantling, recreational and residential areas, if contacted by children in high doses, can trigger neurological and developmental disorders (Ferreira-Baptista and De Miguel 2005; Zheng et al. 2010). Despite the low health hazard indices of Ba, Cd, Co, Ni and Zn in all AEPS sites, these heavy metals can be cumulative and can affect the kidney (Burbure et al. 2003) and other vital human organs, and as such their exposure to children must be avoided.

4.5 Rare earth metals within the AEPS

Based on samples mainly from areas where manual dismantling and separation of electrical electronic equipment takes place, the summary results of the analysis for rare earth metals lost to the soil due to the processing from 14 locations are shown in Table 4.17.

Table 4.17: Summary of rare earth metals lost from AEPS

Rare earth metal	Mean	Std. Dev.	Min	Max	Ref Value
Silver (Ag)	11.55	6.21	1.70	18.90	0.07
Gold (Au)	0.18	0.09	0.07	0.27	0.004
Cadmium (Cd)	8.62	6.35	0.50	26.10	0.20
Cobalt (Co)	21.73	19.20	4.73	73.36	25.00
Europium (Eu)	1.05	0.45	0.51	1.43	1.20
Gallium (Ga)	5.66	3.03	1.10	9.30	15.00
Hafnium (Hf)	14.14	5.24	9.84	22.61	3.00
Lanthanum (La)	16.67	5.30	4.05	23.75	30.00
Magnesium (Mg)	20218.13	19849.29	7639.92	67245.65	23300.00
Manganese (Mn)	737.57	760.21	358.95	3209.38	950.00
Niobiom (Nb)	13.12	5.38	5.70	27.70	20.00
Nickel (Ni)	53.65	26.22	1.80	101.90	75.00
Antimony (Sb)	305.07	307.96	7.20	1090.00	0.200
Scandium (Sc)	4.91	1.15	3.28	6.21	22.00
Tin (Sn)	293.73	208.64	15.70	573.30	2.00
Tantalum (Ta)	2.53	2.14	0.77	6.70	2.00
Thorium (Th)	8.46	4.21	1.45	14.23	9.60
Tungsten (W)	102.72	158.32	9.64	339.50	1.50
Yttrium (Y)	15.00	5.26	4.70	20.90	33.00
Zirconium (Zr)	421.84	116.27	271.30	697.20	165.00

A total of 19 rare earth metals was detected in the soil samples collected within the AEPS. Of the rare earth metals detected and measured, for Ag, Au, Cd, Eu, Hf, Sb, Sn, Ta, W and Zr mean concentration was higher than the reference values (Muller 1969), while the others showed mean concentration lower than that of the reference values. The rare earth metals Cd, Co, Ga, Mg and W are considered by the EU as among the 20 critical metals (EU 2014). Co, Eu, Ga Ni and Mg are also considered within the short and medium term of the US Department of Energy's critical metal strategy (US Department of Energy 2011).

4.5.1 Accumulation of rare earth metals in soils of the AEPS

The results (Figure 4.9) of the assessment of the accumulation of rare earth metals in the AEPS soils are based on the index of geo-accumulation of metals in soil (Equation 2.4). The index was categorized as shown in Table 2.4. Although Sc, Ga, Y, La, Nb as well as Ni, Mn, Mg, Co and Eu were detected in the soils, the measure of accumulation showed only average concentrations of these metals. The mean concentrations of the earth metals Zr, Hf, Cd and Au as well as W, Sn, Ag and Sb were found to be slightly, moderately, severely and extremely accumulated, respectively (Figure 4.9). The slightly to extreme accumulation could be a result of recycling inefficiency, the absence of recycling facilities, crude recycling methods, product design and non-availability of recycling technologies in Ghana, an assumption confirmed by Reck and Graedel (2012) who examined the challenges in metal recycling. The current business-as-usual scenarios of informal e-waste recycling will see more deposits of rare earth metals in the soil and consequently the loss of these metals. This adds to the continuous degradation of the environment, clearing of virgin land for mining and pollution of water and soil and subsequent emission of greenhouse gases (Cui and Forssberg 2003; Reck and Graedel 2012).

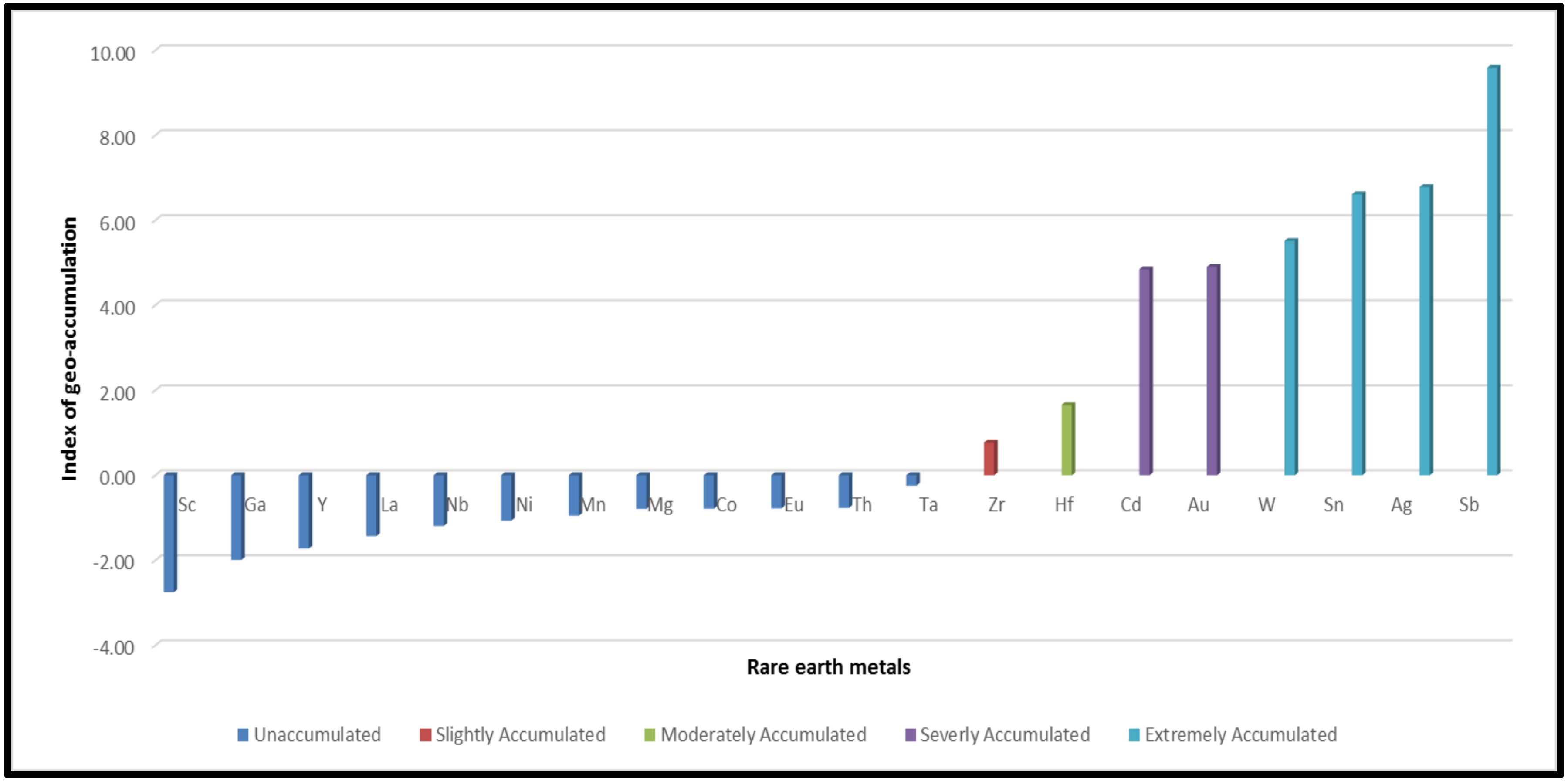

Figure 4.10: Accumulation of rare earth metals in soil at the AEPS

4.6 Framework to Mainstream Informal Recycling Activities

4.6.1 Stakeholders in e-waste management

The assessment of stakeholders in the management of e-waste revealed a fairly complex social network of 21 stakeholders comprising 6 governmental agencies, 11 private groups and 4 groups with both governmental and private characteristics (see Appendix 2a for details and meaning of abbreviations). The social network analysis (Figure 4.11) revealed the formal and informal recyclers as having the strongest influence and highest popularity in the network with the highest betweenness, closeness and eigenvector centralities, although in the pre-assessment of stakeholders the informal recyclers were seen as having low influence (Appendix 2a). This indicates that any initiative or policy should focus on these two stakeholders.

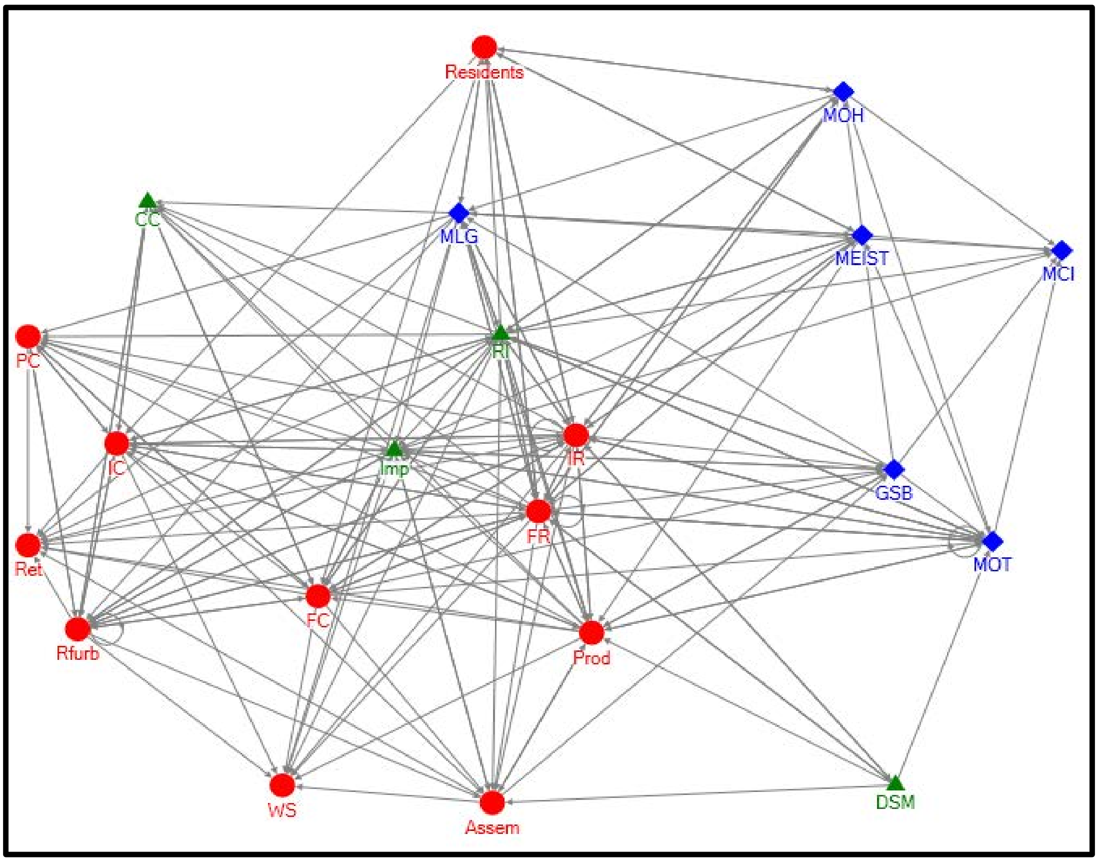

Figure 4.11: Social network of stakeholders in e-waste management in Ghana

4.6.2 E-waste recycling in Ghana

Informal recycling

The field visits and investigation of the e-waste chain revealed a widespread and active network of informal recyclers using considerable manual skills to ensure their existence in the e-waste management process. The e-waste chain showed that e-waste recycling in the informal sector essentially involves collection, sorting and dismantling (Figure 4.12). In addition to the house-to-house collection, the informal recyclers also receive e-waste from repairers and refurbishers with whom they share an active network. The informal e-waste recycling extends beyond the dismantling, as some workers are also are also involved in the extraction of precious metals, and operate with little or no control over their activities while using highly polluting processes detrimental to their health. Although seen as a major contributor to environmental pollution and health risks in the areas they operate in, the (SWOT) analysis reveals strengths, weaknesses, opportunities and threats of the sector compared with the formal sector (Table 4.18).

Formal e-waste recyclers

The study also identified that, despite the strong competition and dominance of the informal recycling sector, a number of formal recycling companies have started operations in Ghana who are also involved in the collection, sorting, separation and extraction of valuable metals from e-waste (Figure 4.12). With the rising e-waste quantities on the one hand, and the draft proposed regulatory requirement expected to soon enter into force on the other, formal recyclers are expected to increase in the e-waste recycling sector. The widespread expectation of these formal sector recyclers is that the management of e-waste will be done in an environmentally sound atmosphere using the best available technologies. Beside the added advantages of formal recycling, there are concerns that the coming on board of formal recycling could come at the expense of informal recyclers which could lead to loss of jobs and livelihoods.

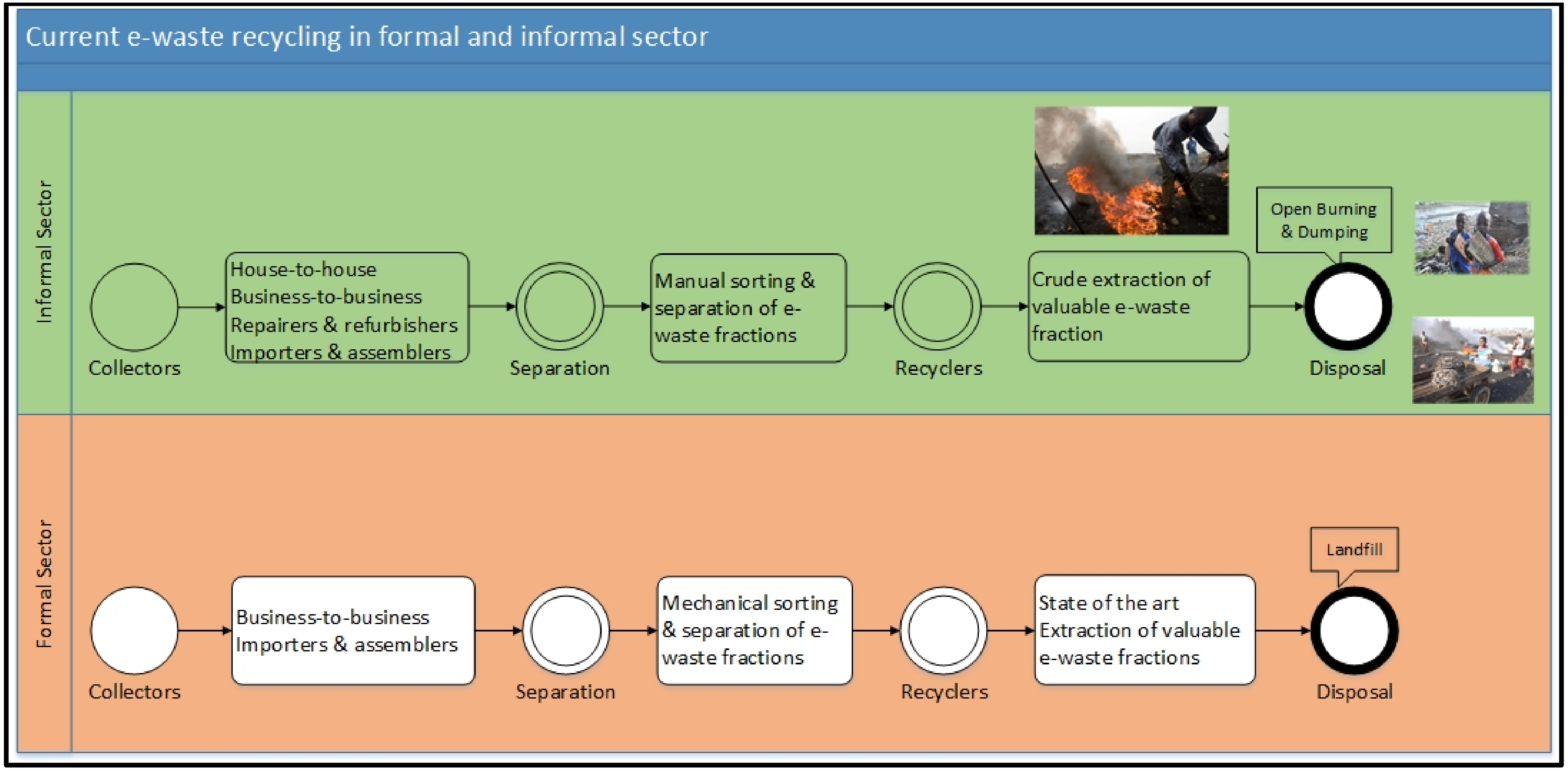

Figure 4.12: Current structure of informal and formal recycling in Ghana

Table 4.18: SWOT analysis of informal and formal recycling sectors

SWOT	Informal Recycling	Formal Recycling
Strengths	✓ Historic role in waste management ✓ High collection rate and efficiency ✓ Low cost of labor in dismantling and sorting techniques compared with mechanical methods	✓ High tech and state-of-the-art facilities and infrastructure for recycling ✓ Superior efficiency in recovery of valuable fractions ✓ Environmentally sound disposal of hazardous fractions
Weaknesses	✓ Moderate efficiency in dismantling and sorting of e-waste ✓ Less efficient in end processing, especially in handling hazardous fraction, which has diverse impacts on humans and the environment.	✓ Low efficiency in collection of e-waste ✓ Huge investments and high operational costs
Opportunities	✓ Potential for improvement in pre-processing through skill development for dismantling and sorting ✓ Opportunities to interface between informal and formal sectors	✓ Potential to improve collection rate ✓ Potential to improve recovery efficiency through technology
Threats	✓ Lack of recognition and support from individuals and governments ✓ Inefficient business practices (“cherry picking” and improper dumping and disposal of non-valuable fractions)	✓ Low amount of raw materials due to informal activities in the collection systems ✓ Competition from other collectors of e-waste. ✓ Inability to access financial markets and assistance

4.6.3 Ghana's proposed e-waste legislation and recycling

Proposed and drafted in 2011, Ghana's hazardous and electronic waste control and management bill seeks to serve as the blueprint for hazardous and e-waste management and disposal in Ghana. An in-depth review of the proposed legislation revealed among other things that the proposed legislation requires:

- Producers and manufactures to register with the EPA
- Producers and importers be responsible for collection and take-back schemes
- Participation of private companies in the recycling of e-waste
- Community and municipal collection points be setup.

Furthermore, the proposed legislation demands recyclers to ensure environmentally sound recycling practices. With the responsibility of e-waste collection to be shifted to producers, importers and manufactures, and recycling of e-waste to be done in an environmentally sound manner while responsibilities of the informal sector are not defined, there are concerns that in an attempt to meet the demands of the draft legislation, there could be possible ripple effects. These could be loss of jobs in the informal sector, loss of livelihoods for dependents, and strain on the ability to collect this waste in areas difficult to access. Kojima *et al*. (2009) revealed that systems like those proposed, i.e. a similar form of extended producer responsibilities, have failed in countries where there are highly diverse, resourceful and skilled actors in the informal sector. This therefore calls for options that will be based not only on the weakness of the informal recyclers and the strength of formal recyclers but on a holistic and sustainable approach that will harness the strengths of both recyclers.

4.6.4 The way forward: sustainable e-waste management

Ghana's e-waste sector is dominated by the informal sector with some formal sector players entering the e-waste market. The role of both informal and formal actors remains critical if e-waste is to be managed sustainably bearing in mind the strengths, weaknesses, opportunities and threats of both sectors (Table 4.17). In the informal sector, e-waste is extensively collected and manually dismantled but recycled in an environmentally unsound manner. In contrast, in the formal sector e-waste is insufficiently collected but recycled in an environmentally sound manner. Against this background, there is the need to identify options that will mainstream and formalize the activities of e-waste management in Ghana (Figure 4.12).

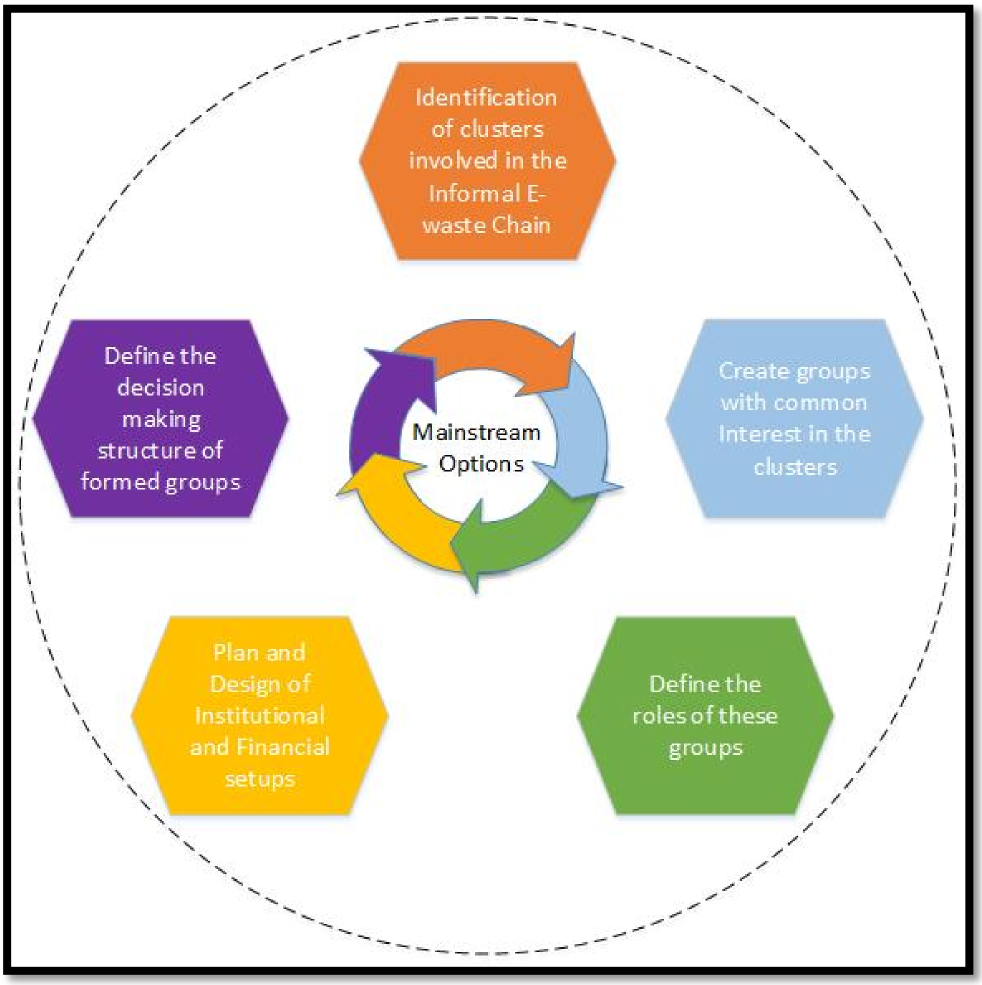

Figure 4.13: Initial options to mainstream informal e-waste activities

When options have been identified, associations need to be formed and registered and their business professionalized. This will provide the informal sector with the necessary acceptance by society and the ability to access the financial market. These two factors were stated as presently non-existent by the respondents during the survey. There is also a need to define the levels on which the groups can operate. Both sectors are involved in the same chain of activities but possess different strengths, weaknesses, and opportunities (Table 4.17). Acknowledging these aspects, this study proposes a structure as illustrated in Figure 4.14 as the way forward if e-waste is to be managed in an environmentally sustainable manner. This structure could provide a mutual support system for the activities of both formal and informal sectors, and a balance between cheap labor-intensive operations in the informal sector and environmentally sound efficient, mechanized operations in the formal sector.

The proposed scenario recommends collection and some preliminary manual dismantling to be done by the informal sector while the mechanized dismantling and recycling are done by the formal sector. This will ensure mutual gains for all actors in the chain as a result of trade of materials between the informal and formal sectors. In addition, it is clear that this will help do away with crude and primitive recycling methods and provide better resource management while maintaining and creating better and greener jobs in both the informal and formal sector. The proposed structure and sustainability of the structure will hinge on optimizing the flow of resources and putting systems in place to check pilferage from one end of the chain to the other.

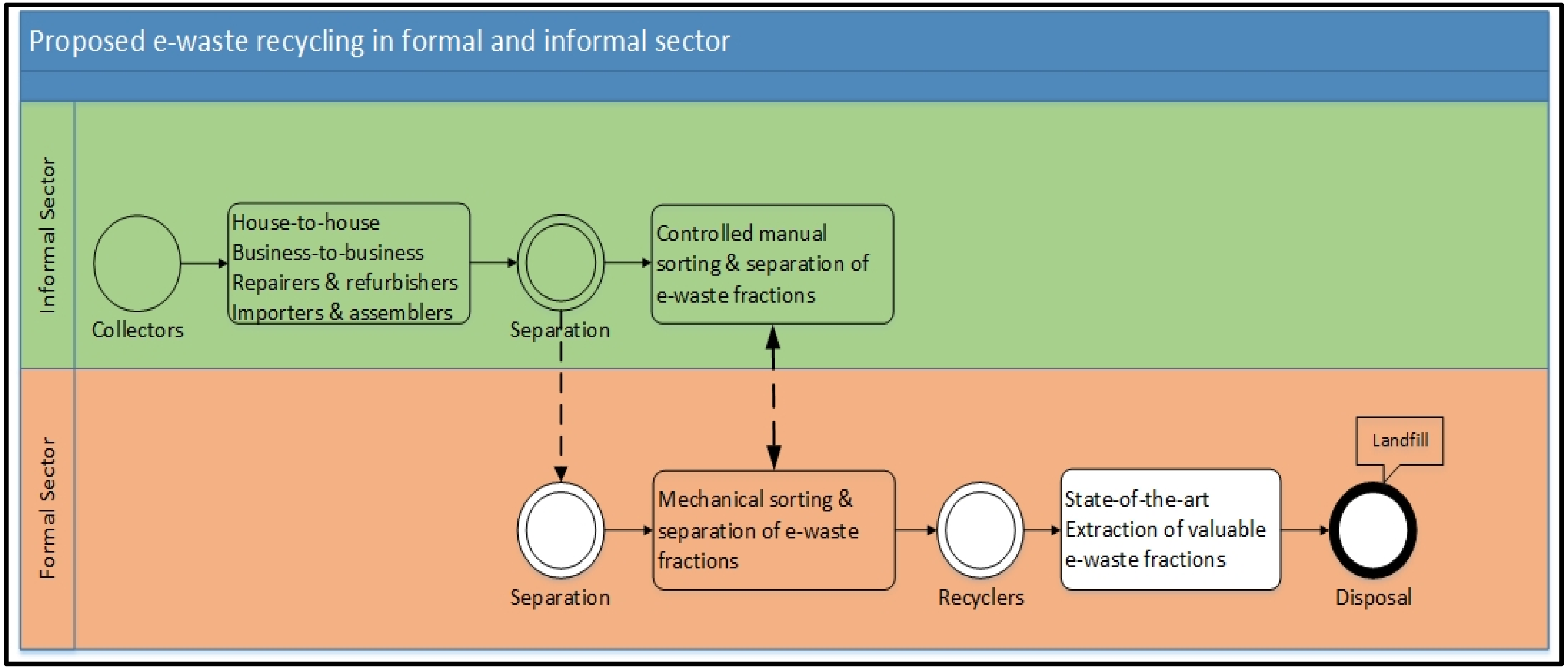

Figure 4.14: Proposed future scenario of e-waste recycling

Regulations and incentives

Considering the dominance of the informal sector in e-waste management in Ghana, it is obvious that the goal of mainstreaming will not be met if proper regulations, policies and incentives are not in place. Attempts to mainstream and integrate the informal sector in the management of e-waste in developing countries have shown that radical governmental regulations and policies aimed at forbidding the operations of the informal sector have been difficult to achieve. Therefore, policy interventions and incentives are suggested if the proposed structure is to be implemented. Incentives such as subsidies or insurance schemes to those complying with health and environmental norms and promotion of the marketing of such products through certification mechanisms could help reduce the possibility of “free riders”, as most of the actors will want to market their products and profit from subsidies and insurance schemes. In addition, critical to the long-term sustainability of the proposed structure is the need to motivate e-waste generators to apply minimum standards to their e-waste disposal. The role and responsibilities of producers, manufacturers and importers in the management of e-waste should be defined. Awareness and educational measures are also needed to provide accompanying guidance to enhance enforcement of these initiatives.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Factors affecting e-waste management

An overview of the current e-waste management and governance structure revealed that the current system is not effective in minimizing the public health and environmental concerns of the activities of e-waste recyclers. The lack of e-waste-specific legislation and policies in the management structure, the uncoordinated institutional framework structure and inadequate management infrastructure, lack of skills and technical capabilities, lack of education and awareness of consumers and recyclers of electrical and electronic materials all affect the efficient management of e-waste.

5.1.2 Environmental impacts from informal e-waste recycling

The environmental impacts of e-waste recycling was evaluated by assessing the concentration and extent of heavy metal contamination in the soils of the AEPS, and the possible ecological risks the contamination poses to aquatic and terrestrial species. The following conclusions were drawn:

- ❖ The results of the analysis reveal that the heavy metal concentrations were ubiquitous within the AEPS, and that the concentrations in the soils exceeded the minimum and action required limits of both the Dutch and Canadian Soil Quality and Guidance Values by 10 to 1000 times.
- ❖ Contamination factor, degree of contamination and potential ecological risk indices employed to determine the level and extent of heavy metal pollution in soils at the AEPS showed that the area is contaminated with nine heavy metals, with Cd, Cu, Hg, Pb and Zn being the major contributors to the contamination in the soil and environment.
- ❖ Geostatistical analysis showed that degree of contamination and potential ecological risk values exhibited normal distribution after log transformation, spatial variation through the entropy voronoi map and spatial autocorrelation.

Kriging requirements of normality, spatial variation and autocorrelation were met before kriging of spatial distribution maps.

- ❖ The spatial distribution map reveals that the burning and dismantling areas show the highest degree of contamination, and that the contamination extends beyond the burning and dismantling areas to areas close to school, clinic, residential and worship areas.
- ❖ The contamination and levels of the heavy metals measured in the soils at the AEPS pose potential ecological risks to both terrestrial and aquatic species within parts of the AEPS.

5.1.3 Health impacts from e-waste recycling

The health impacts from the e-waste recycling activities within the AEPS were assessed by evaluating both the carcinogenic and non-carcinogenic health risks posed by exposure to heavy metal (Ba, Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn) to local inhabitants, specifically children under 6 years who are more susceptible to heavy metal exposure. The following conclusion can be drawn:

- ❖ In the AEPS, the exposure pathway that results in the highest level of health risks to children exposed to the investigated heavy metals is ingestion of particles, with Cr, Pb and Cu being of most concern in all three exposure pathways.
- ❖ The hazard indices of Ba, Cd, Co, Ni and Zn were less than 1, thus indicating a relative absence of non-carcinogenic health risks related to the exposure pathways ingestion, dermal contact and inhalation.
- ❖ The hazard indices of Cr and Pb were above the threshold value of 1 for non-carcinogenic hazard risks indicating possible triggers of neurological and developmental disorders in children.
- ❖ The hazard indices for the four carcinogenic heavy metals Cd, Co, Cr and Ni were below the threshold range of 10^{-4} to 10^{-6} indicating a relative absence of carcinogenic health risks. The index, however, of Cr in all areas is of concern as it is closest to the threshold range.

- The results of the health risk assessment of the exposure of heavy metals are affected by some degree of uncertainty related primarily to estimates of toxicity and exposure parameters.
- The degree of uncertainty in the health risk assessment does not prohibit the use of the assessment to confirm or reject the existence of unacceptable levels.

5.1.4 Rare earth metals

The possible loss of rare earth metals from the informal crude e-waste processing methods at Agbogbloshie was examined, and the results lead to the following conclusions:

- The primitive recycling methods of e-waste at the AEPS contribute to the loss of rare earth metals inherent in waste electrical electronic equipment.
- 19 rare earth metals were identified in the analysis of soil samples collected from the AEPS.
- Of the 19 critical metals identified in the soils at the AEPS, 11 were assessed based on the index of geo-accumulation and were found to be not accumulated in the soil, (Sc, Ga, Y, La, Nb, Ni, Mn, Mg, Co, Eu, Th and Ta).
- Zr, Hf, Cd, Au, W, Sn, Ag and Sb had geo-accumulation index values classified between slightly and extreme accumulation.

5.1.5 Mainstreaming formal and informal recycling

The objective of identifying options to mainstream the activities of informal e-waste actors was assessed by examining the stakeholders, their social networks, and their influence, and identifying the options to mainstream the activities of the informal and formal sectors in e-waste management. The following conclusion can be made:

- The formal and informal recyclers are the most influential stakeholders as they showed the highest betweeness, closeness and eigenvector centralities, which are the measures of importance and influence in the social network.
- The strength and opportunities of both formal and informal sectors could complement each other and help harness the potential of recycling of valuable

metals from e-waste, while also reducing the threats and weaknesses posed by each sector.

- The potential of formal recyclers is seemingly under-utilized, as the business environment is not attractive and is faced with insufficient investments that cannot meet the operational costs.
- The mainstreaming of activities in the informal sector and ensuring collaboration with the formal sector is critical to establish an environmentally and economically sustainable recycling model for e-waste management in Ghana.

5.2 Recommendation

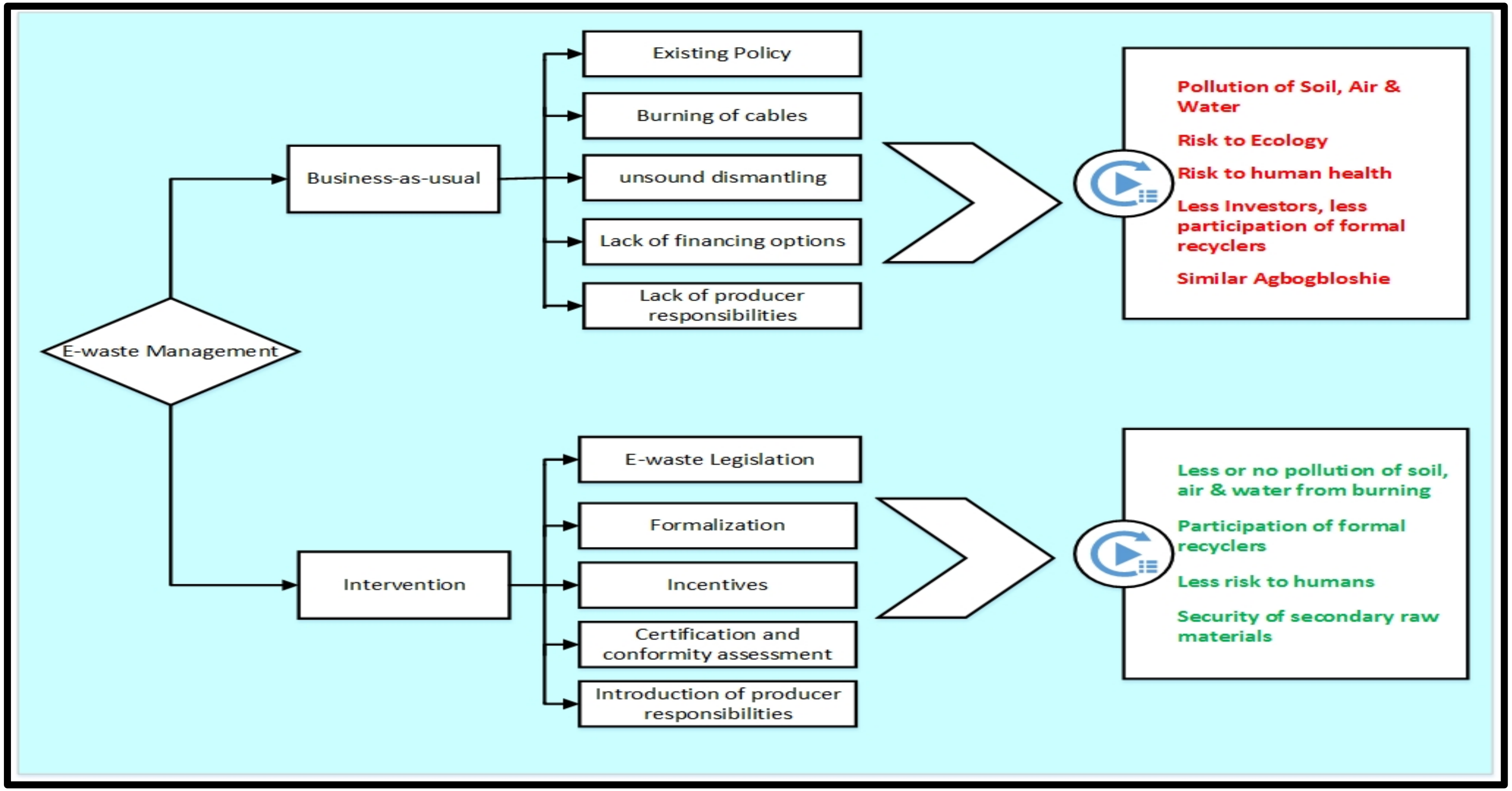

Figure 5.1: Decision options for e-waste management

Figure 5.1 depicts deductions made from the research and presents scenario options in the e-waste management decisions. It shows that maintaining the status quo, i.e. the business-as-usual scenario, will result in the pollution of the environment, risk to ecology and health, less participation of formal recyclers, and a source of encouragement for similar sites like Agbogbloshie springing up in all parts of the country. The ability to introduce intervention measures such as implementation of the e-waste bill, formalization of the informal sector, provision of incentives, certification and introduction of producer responsibilities can also result in reduced pollution of the environment and, participation of formal recyclers, and can ensure security of secondary raw materials. On this basis, the following recommendations are made:

5.2.1 E-waste management and governance

Based on the factors identified in this study as affecting the management and governance of e-waste and the quest to ensure sustainable e-waste management, the following recommendations are made:

- **Effective institutional structure:** To be able to improve upon the overall governance of e-waste in Ghana, an effective institutional structure is vital. This will depend largely on Ghana’s ability to build on the existing public institutions and to orientate their respective capabilities to focus on the ensuring effective management of e-waste without comprising on their core functions.
- **Enhanced law enforcement:** The Ghanaian government needs to take steps to allot adequate and appropriate resources to enforce existing environmental laws and regulations. Increasing the accountability of local governments and environmental regulators and instituting greater public awareness are critical for enhanced law enforcement.
- **Improved collaboration:** With Ghana’s e-waste crisis being not only local but also global, effective and improved collaboration, i.e. both local and international, between agencies or countries could be the most effective way to resolve the e-waste crisis in Ghana.

5.2.2 Impacts from e-waste recycling in Ghana

Based on the revealed widespread contamination of the AEPS with heavy metals, the potential ecological and health risks to the environment, humans, and aquatic and terrestrial species, it is recommended that:

- ❖ Further studies need to be conducted on the activities of informal e-waste recyclers, and environmentally sustainable ways proposed to efficiently recover valuable metals from e-waste in Ghana.
- ❖ Given the level and spatial extent of the contamination, the ecological and health risks, urgent precautionary and remediation measures must be taken in order to prevent the further spread of the heavy metal contamination if the proposed ecological restoration earmark within the AEPS is to be implemented.
- ❖ The results of the health risk assessment for the exposure of heavy metals to children within the AEPS were affected by some degree of uncertainty, which is mainly associated with toxicity estimate values, and only few exposure parameters in Ghana. This underlines the need for further research into exposure and transport factors at the AEPS that would help to reduce the currently considerable uncertainty associated with the risk assessment.

5.2.3 Mainstreaming informal e-waste recycling

The mainstreaming, integration and formalization of the informal recycling sector present one of the best options for sustainable e-waste management in Ghana. The proposed framework could be applicable in most developing countries where informal actors dominate the management of e-waste recycling. It is recommended that:

- ❖ The informal actors role in the management and governance chain of e-waste should be well defined in future e-waste-specific legislation and actors in the sector should be empowered to promote and be part of a cleaner recycling environment.
- ❖ The enforcement and implementation of the proposed integration of the informal sector framework and the entering of the formal recyclers into the e-waste sector should safeguard the livelihoods of the informal workers.

- The proposal to incorporate or mainstream the informal sector into the e-waste management could be socially acceptable, economically feasible and environmentally sound. It is however recommended that the government and environmental managers should recognize the potential of informal actors and make it easier for them to participate in the process.
- The survival and sustainability of the proposed framework will also depend on finding proactive leaders in the informal sector, highlighting the field opportunities and building trust at all levels among all stakeholders.

6 REFERENCES

Adjei-Boateng D, Obirikorang KA, Amisah S (2010) Bioaccumulation of heavy metals in the tissue of the clam Galatea paradoxa and sediments from the Volta Estuary, Ghana.

Amoyaw-Osei Y, Agyekum OO, Pwamang JA, et al (2011) Informal e-waste management in Ghana-economic impacts and feasibility of inter-national recycling co-operations.

Amuno SA (2013) Potential Ecological Risk of Heavy Metal Distribution in Cemetery Soils. Water Air Soil Pollut 224:1–12. doi: 10.1007/s11270-013-1435-2

Asante KA, Adu-Kumi S, Nakahiro K, et al (2011) Human exposure to PCBs, PBDEs and HBCDs in Ghana: Temporal variation, sources of exposure and estimation of daily intakes by infants. Environment International 37:921–928. doi: 10.1016/j.envint.2011.03.011

Asante KA, Agusa T, Biney CA, et al (2012) Multi-trace element levels and arsenic speciation in urine of e-waste recycling workers from Agbogbloshie, Accra in Ghana. Science of The Total Environment 424:63–73. doi:10.1016/j.scitotenv. 2012.02.072

Atasu A, Subramanian R (2012) Extended Producer Responsibility for E-Waste: Individual or Collective Producer Responsibility? Production and Operations Management 21:1042–1059.

ATE ATE (2012) Identification of the magnitude of the electrical and electronic (e-Waste) situation in South Africa: a strategic approach to International chemicals management (SAICM) e-Waste as an Emerging policy issue.

Atiemo SM, Ofosu FG, Aboh IK, Kuranchie-Mensah H (2012) Assessing the heavy metals contamination of surface dust from waste electrical and electronic equipment (e-waste) recycling site in Accra, Ghana. Research Journal of Environmental and Earth Sciences 4:605–611.

Bai J, Cui B, Chen B, et al (2011) Spatial distribution and ecological risk assessment of heavy metals in surface sediments from a typical plateau lake wetland, China. Ecological Modelling 222:301–306. doi: 10.1016/j.ecolmodel.2009.12.002

Banat KM, Howari FM, Al-Hamad AA (2005) Heavy metals in urban soils of central Jordan: Should we worry about their environmental risks? Environmental Research 97:258–273. doi: 10.1016/j.envres.2004.07.002

Bowen HJM (1979) Environmental chemistry of the elements. Academic Press.

Brigden K, Labunska I, Santillo D, Allsopp M (2005) Recycling of electronic wastes in China and India: workplace and environmental contamination.

Brigden K, Labunska I, Santillo D, Johnston P (2008) Chemical contamination at e-waste recycling and disposal sites in Accra and Korforidua, Ghana.

Brook RD, Franklin B, Cascio W, et al (2004) Air Pollution and Cardiovascular Disease A Statement for Healthcare Professionals From the Expert Panel on Population and Prevention Science of the American Heart Association. Circulation 109:2655–2671. doi: 10.1161/01.CIR.0000128587.30041.C8

Bryan G, Gibbs PE (1983) Heavy metals in the Fal estuary, Cornwall; a study of long-term contamination by mining waste and its effects on estuarine organisms. Marine Biological Association Plymouth, England, Occasional Publication No 2,(02 Cb BRY) 112.

Bryan GW (1971) The Effects of Heavy Metals (other than Mercury) on Marine and Estuarine Organisms. Proceedings of the Royal Society of London B: Biological Sciences 177:389–410. doi: 10.1098/rspb.1971.0037

Burbure C de, Buchet J-P, Bernard A, et al (2003) Biomarkers of Renal Effects in Children and Adults with Low Environmental Exposure to Heavy Metals. Journal of Toxicology and Environmental Health, Part A 66:783–798. doi: 10.1080/15287390306384

Caeiro S, Costa MH, Ramos TB, et al (2005) Assessing heavy metal contamination in Sado Estuary sediment: An index analysis approach. Ecological Indicators 5:151–169. doi: 10.1016/j.ecolind.2005.02.001

Cahn MD, Hummel JW, Brouer BH (1994) Spatial Analysis of Soil Fertility for Site-Specific Crop Management. Soil Science Society of America Journal 58:1240. doi: 10.2136/sssaj1994.03615995005800040035x

Cambardella CA, Moorman TB, Parkin TB, et al (1994) Field-Scale Variability of Soil Properties in Central Iowa Soils. Soil Science Society of America Journal 58:1501. doi: 10.2136/sssaj1994.03615995005800050033x

Caravanos J, Clark E, Fuller R, Lambertson C (2011) Assessing Worker and Environmental Chemical Exposure Risks at an e-Waste Recycling and Disposal Site in Accra, Ghana. Journal of Health and Pollution. doi: 10.5696/jhp.v1i1.22

Cattle JA, McBratney AB, Minasny B (2002) Kriging Method Evaluation for Assessing the Spatial Distribution of Urban Soil Lead Contamination. Journal of Environment Quality 31:1576. doi: 10.2134/jeq2002.1576

Chancerel P, Meskers CEM, HagelÃ¼ken C, Rotter VS (2009) Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment. Journal of Industrial Ecology 13:791–810. doi:10.1111/j.1530-9290.2009.00171.x

Chen A, Dietrich KN, Huo X, Ho S (2011) Developmental Neurotoxicants in E-Waste: An Emerging Health Concern. Environ Health Perspect 119:431–438. doi:10.1289/ehp.1002452

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

Ciocoiu CN, Täriu V (2012) The Role Of Informal Sector Within Weee Management Systems: A Romanian Perspective. Theoretical and Empirical Researches in Urban Management 7:27–38.

Cui J, Forssberg E (2003a) Mechanical recycling of waste electric and electronic equipment: a review. Journal of Hazardous Materials 99:243–263. doi: 10.1016/S0304-3894(03)00061-X

Cui J, Forssberg E (2003b) Mechanical recycling of waste electric and electronic equipment: a review. Journal of Hazardous Materials 99:243–263. doi: 10.1016/S0304-3894(03)00061-X

Dallinger R, Prosi F, Segner H, Back H (1987) Contaminated food and uptake of heavy metals by fish: a review and a proposal for further research. Oecologia 73:91–98. doi: 10.1007/BF00376982

Dalrymple I, Wright N, Kellner R, et al (2007) An integrated approach to electronic waste (WEEE) recycling. Circuit World 33:52–58. doi: 10.1108/03056120710750256

Donald JW (1992) Bamako Convention as a Solution to the Problem of Hazardous Waste Exports to Less Developed Countries, The. Colum J Envtl L 17:419.

Duker AA, Stein A, Hale M (2006) A statistical model for spatial patterns of Buruli ulcer in the Amansie West district, Ghana. International Journal of Applied Earth Observation and Geoinformation 8:126–136. doi: 10.1016/j.jag.2005.06.013

El-Nakib I (2012) Reverse Logistics: A Comparison of Electronic Waste Recycling Between Switzerland and Egypt. In: Global Conference on Operations and Supply Chain Management-GCOM.

EU (2014) Report on Critical Raw Materials for the EU.

EU WEEE Directive (2002) 96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Official Journal of the European Union L 37:24–38.

Ferreira-Baptista L, De Miguel E (2005) Geochemistry and risk assessment of street dust in Luanda, Angola: A tropical urban environment. Atmospheric Environment 39:4501–4512. doi: 10.1016/j.atmosenv.2005.03.026

Forge S (2007) Powering down: remedies for unsustainable ICT. foresight 9:3–21.

Franklin AL (2000) An examination of bureaucratic reactions to institutional controls. Public Performance & Management Review 8–21.

Frazzoli C, Orisakwe OE, Dragone R, Mantovani A (2010) Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. Environmental Impact Assessment Review 30:388–399. doi: 10.1016/j.eiar.2009.12.004

Fu J, Zhou Q, Liu J, et al (2008) 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. doi: 10.1016/j.chemosphere.2007.11.065

Gartner I (2007) Gartner Says Worldwide Mobile Phone Sales Increased 16 Per Cent in 2007. http://www.gartner.com/newsroom/id/612207. Accessed 26 Jul 2014

Ghrefat H, Yusuf N (2006) Assessing Mn, Fe, Cu, Zn, and Cd pollution in bottom sediments of Wadi Al-Arab Dam, Jordan. Chemosphere 65:2114–2121. doi: 10.1016/j.chemosphere.2006.06.043

Goosey M (2004) End-of-life electronics legislation–an industry perspective. Circuit World 30:41–45.

Goovaerts P (1999) Geostatistics in soil science: state-of-the-art and perspectives. Geoderma 89:1–45. doi: 10.1016/S0016-7061(98)00078-0

Goovaerts P (1998) Geostatistical tools for characterizing the spatial variability of microbiological and physico-chemical soil properties. Biology and Fertility of soils 27:315–334.

Gottberg A, Morris J, Pollard S, et al (2006) Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector. Science of The Total Environment 359:38–56. doi: 10.1016/j.scitotenv.2005.07.001

Grant K, Goldizen FC, Sly PD, et al (2013) Health consequences of exposure to e-waste: a systematic review. The Lancet Global Health 1:e350–e361. doi: 10.1016/S2214-109X(13)70101-3

Grant R, Oteng-Ababio M (2012) Mapping the Invisible and Real "African" Economy: Urban E-Waste Circuitry. Urban Geography 33:1–21. doi: 10.2747/0272-3638.33.1.1

GSS (2010) 2010 POPULATION AND HOUSING CENSUS.

Guo G, Wu F, Xie F, Zhang R (2012) Spatial distribution and pollution assessment of heavy metals in urban soils from southwest China. Journal of Environmental Sciences 24:410–418. doi: 10.1016/S1001-0742(11)60762-6

Gupta KS (2011) E-waste Management: Teaching how to Reduce, Reuse and Recycle For Sustainable Development-Need of Some Educational strategies. Journal of Education and Practice 2:74–85.

Hakanson L (1980) An ecological risk index for aquatic pollution control.a sedimentological approach. Water Research 14:975–1001. doi: 10.1016/0043-1354(80)90143-8

Ha NN, Agusa T, Ramu K, et al (2009) Contamination by trace elements at e-waste recycling sites in Bangalore, India. Chemosphere 76:9–15. doi: 10.1016/j.chemosphere.2009.02.056

Herat S (2007) Sustainable Management of Electronic Waste (e-Waste). Clean Soil Air Water 35:305–310. doi: 10.1002/clen.200700022

Hoek G, Beelen R, de Hoogh K, et al (2008) A review of land-use regression models to assess spatial variation of outdoor air pollution. Atmospheric Environment 42:7561–7578. doi: 10.1016/j.atmosenv.2008.05.057

Huo X, Peng L, Xu X, et al (2007) Elevated Blood Lead Levels of Children in Guiyu, an Electronic Waste Recycling Town in China. Environ Health Perspect 115:1113–1117. doi: 10.1289/ehp.9697

Hurst C (2010) China's Rare Earth Elements Industry: What Can the West Learn?

Imperato M, Adamo P, Naimo D, et al (2003) Spatial distribution of heavy metals in urban soils of Naples city (Italy). Environmental Pollution 124:247–256. doi: 10.1016/S0269-7491(02)00478-5

INTERPOL (2009) Electronic Waste and Organized Crime, Assessing the link. Interpol

Itai T, Otsuka M, Asante KA, et al (2014) Variation and distribution of metals and metalloids in soil/ash mixtures from Agbogbloshie e-waste recycling site in Accra, Ghana. Science of the Total Environment 470:707–716.

Jerrett M, Burnett RT, Ma R, et al (2005) Spatial Analysis of Air Pollution and Mortality in Los Angeles: Epidemiology 16:727–736. doi: 10.1097/01.ede.0000181630.15826.7d

Kurian J (2007) Electronic waste management in India–issues and strategies. In: Proceedings of the Eleventh International Waste Management and Landfill Symposium.

Jun-hui Z, Hang M (2009) Eco-toxicity and metal contamination of paddy soil in an e-wastes recycling area. Journal of Hazardous Materials 165:744–750. doi: 10.1016/j.jhazmat.2008.10.056

Kahhat R, Kim J, Xu M, et al (2008) Exploring e-waste management systems in the United States. Resources, Conservation and Recycling 52:955–964. doi: 10.1016/j.resconrec.2008.03.002

Kaminsky HS (1992) Assessment of the Bamako Convention on the Ban of Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa. Geo Int'l Envtl L Rev 5:77.

Kartal Ş, Aydın Z, Tokalıoğlu Ş (2006) Fractionation of metals in street sediment samples by using the BCR sequential extraction procedure and multivariate statistical elucidation of the data. Journal of Hazardous Materials 132:80–89. doi: 10.1016/j.jhazmat.2005.11.091

Keelson KB (2014) Prediction of Post-Closure Water Balance for Monolithic Soil Covers at Waste Disposal Sites in the Greater Accra Metropolitan Area of Ghana. International Journal of Engineering and Technology 4:96–106.

Kerry R, Oliver MA (2004) Average variograms to guide soil sampling. International Journal of Applied Earth Observation and Geoinformation 5:307–325. doi: 10.1016/j.jag.2004.07.005

Khan S, Cao Q, Zheng YM, et al (2008) Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. Environmental Pollution 152:686–692. doi: 10.1016/j.envpol.2007.06.056

Khetriwal DS, Kraeuchi P, Widmer R (2009) Producer responsibility for e-waste management: Key issues for consideration – Learning from the Swiss experience. Journal of Environmental Management 90:153–165. doi:10.1016/j.jenvman.2007.08.019

Kiddee P, Naidu R, Wong MH (2013) Electronic waste management approaches: An overview. Waste Management. doi: 10.1016/j.wasman.2013.01.006

Kojima M, Yoshida A, Sasaki S (2009) Difficulties in applying extended producer responsibility policies in developing countries: case studies in e-waste recycling in China and Thailand. Journal of Material Cycles and Waste Management 11:263–269. doi: 10.1007/s10163-009-0240-x

Korre A, Durucan S, Koutroumani A (2002) Quantitative-spatial assessment of the risks associated with high Pb loads in soils around Lavrio, Greece. Applied Geochemistry 17:1029–1045. doi: 10.1016/S0883-2927(02)00058-6

Krueger J, Selin H (2002) Governance for Sound Chemicals Management: The Need for a More Comprehensive Global Strategy. Global Governance 8:323.

Kumi-Boateng B (2007) Assessing Spatial Distribution of Arsenic Concentration from gold mine for environmental Management at Obuasi, Ghana. Masters Thesis, ITC and KNUST

Kyere VN, Atiemo SM, Benefo TD, et al (2013) Exploratory Assessment of E-Waste Governance Structures in Africa: A Case Study of Ghana.

Leung A, Cai ZW, Wong MH (2006) Environmental contamination from electronic waste recycling at Guiyu, southeast China. J Mater Cycles Waste Manag 8:21–33. doi: 10.1007/s10163-005-0141-6

Leung AOW, Chan JKY, Xing GH, et al (2010) Body burdens of polybrominated diphenyl ethers in childbearing-aged women at an intensive electronic-waste recycling site in China. Environ Sci Pollut Res 17:1300–1313. doi: 10.1007/s11356-010-0310-6

Leung AOW, Duzgoren-Aydin NS, Cheung KC, Wong MH (2008) Heavy Metals Concentrations of Surface Dust from e-Waste Recycling and Its Human Health Implications in Southeast China. Environmental Science & Technology 42:2674–2680. doi: 10.1021/es071873x

Leung AOW, Luksemburg WJ, Wong AS, Wong MH (2007) Spatial Distribution of Polybrominated Diphenyl Ethers and Polychlorinated Dibenzo-p-dioxins and Dibenzofurans in Soil and Combusted Residue at Guiyu, an Electronic Waste Recycling Site in Southeast China. Environ Sci Technol 41:2730–2737. doi: 10.1021/es0625935

Lim H-S, Lee J-S, Chon H-T, Sager M (2008) Heavy metal contamination and health risk assessment in the vicinity of the abandoned Songcheon Au–Ag mine in Korea. Journal of Geochemical Exploration 96:223–230. doi:10.1016/j.gexplo.2007.04.008

Lindhqvist T (2000) Extended producer responsibility in cleaner production: policy principle to promote environmental improvements of product systems. International Institute for Industrial Environmental Economics (Internationella miljöinstitutet), Univ.

Lin N (1999) Social Networks and Status Attainment. Annual Review of Sociology 25:467–487.

Liu W, Zhao J, Ouyang Z, et al (2005) Impacts of sewage irrigation on heavy metal distribution and contamination in Beijing, China. Environment International 31:805–812. doi: 10.1016/j.envint.2005.05.042

Liu X (2006) Electrical and electronic waste management in China: progress and the barriers to overcome. Waste Management & Research 24:92–101. doi: 10.1177/0734242X06062499

Liu X, Wu J, Xu J (2006) Characterizing the risk assessment of heavy metals and sampling uncertainty analysis in paddy field by geostatistics and GIS. Environmental Pollution 141:257–264. doi: 10.1016/j.envpol.2005.08.048

Loska K, Cebula J, Pelczar J, et al (1997) Use of enrichment, and contamination factors together with geoaccumulation indexes to evaluate the content of Cd, Cu, and Ni in the Rybnik water reservoir in Poland. Water, Air, and Soil Pollution 93:347–365.

Loska K, Wiechuła D, Korus I (2004) Metal contamination of farming soils affected by industry. Environment International 30:159–165. doi: 10.1016/S0160-4120(03) 00157-0

Lu X, Wang L, Lei K, et al (2009) Contamination assessment of copper, lead, zinc, manganese and nickel in street dust of Baoji, NW China. Journal of Hazardous Materials 161:1058–1062. doi: 10.1016/j.jhazmat.2008.04.052

Manhart A, Osibanjo O, Aderinto A, Prakash S (2011) Informal e-waste management in Lagos, Nigeria–socio-economic impacts and feasibility of inter-national recycling co-operations.

Manhart A, Schleicher T, Degreif S (2014) Global Circular Economy of Strategic Metals–the Best-of-two-Worlds Approach (Bo2W). Oeko - Institut e.V.

Matthews HS, McMichael FC, Hendrickson CT, Hart DJ (1997) Disposition and end-of-life options for personal computers. Carnegie Mellon University Green Design Initiative Technical Report

Maxwell Ms (2013) Sustainable Consumption. In: Kauffman J, Lee K-M (eds) Handbook of Sustainable Engineering. Springer Netherlands, pp 691–705

McKone TE, Daniels JI (1991) Estimating human exposure through multiple pathways from air, water, and soil. Regulatory Toxicology and Pharmacology 13:36–61.

Meza-Figueroa D, De la O-Villanueva M, De la Parra ML (2007) Heavy metal distribution in dust from elementary schools in Hermosillo, Sonora, México. Atmospheric Environment 41:276–288. doi: 10.1016/j.atmosenv.2006.08.034

Müller E, Schluep M, Widmer R, et al (2009) Assessment of e-waste flows: a probabilistic approach to quantify e-waste based on world ICT and development indicators. In: R’09 Twin World Congress. pp 14–16

Muller G (1969) Index of geoaccumulation in sediments of the Rhine River. Geojournal 2:108–118.

Mureithi M, Waema T (2008) E-waste Management in Kenya. Kenya ICT Action Network (KICTANet), Kenya. Available from< http://ewasteguide. Info/Waema_2008_ KICTANet>[Last accessed 9 September 2009]

Ni H-G, Zeng E. (2009) Law enforcement and global collaboration are the keys to containing e-waste tsunami in China. in Environmental Science & Technology Vol. 43:pp. 3991–3994.

Nnorom IC, Osibanjo O (2008a) Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resources, Conservation and Recycling 52:843–858. doi:10.1016/ j.resconrec.2008.01.004

Nnorom IC, Osibanjo O (2008b) Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resources, Conservation and Recycling 52:843–858. doi: 10.1016/j.resconrec.2008.01.004

Ogungbuyi O, Nnorom IC, Osibanjo O, Schluep M (2012) E-Waste Country Assessment Nigeria. Secretariat of the Basel Convention

Okolo I (2013) E-waste management in Accra.

Ongondo FO, Williams ID, Cherrett TJ (2011) How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Management 31:714–730. doi: 10.1016/j.wasman.2010.10.023

Otchere FA (2004) Heavy metals concentrations and burden in the bivalves (Anadara (Senilia) senilis, Crassostrea tulipa and Perna perna) from lagoons in Ghana: Model to describe mechanism of accumulation/excretion. African Journal of Biotechnology 2:280–287.

Oteng-Ababio M (2010) E-waste: an emerging challenge to solid waste management in Ghana. International Development Planning Review 32:191–206. doi: 10.3828/idpr.2010.02

Oteng-Ababio M (2012a) When Necessity Begets Ingenuity: E-Waste Scavenging as a Livelihood Strategy in Accra, Ghana.

Oteng-Ababio M (2012b) The Role of the Informal Sector in Solid Waste Management in the Gama, Ghana: Challenges and Opportunities. Tijdschrift voor economische en sociale geografie 103:412–425. doi: 10.1111/j.1467-9663.2011.00690.x

Otsuka M, Itai T, Asante KA, et al (2012) Trace element contamination around the e-waste recycling site at agbogbloshie, Accra City, Ghana. Interdisciplinary Studies on Environmental Chemistry—Environ Pollut Ecotoxicol 6:161–167.

Ott WR (1978) Environmental indices: theory and practice.

Prakash S, Manhart A, Amoyaw-Osei Y, Agyekum OO (2010) Socio-economic assessment and feasibility study on sustainable e-waste management in Ghana.

Puckett J, Smith T (2002) Exporting harm: the high-tech trashing of Asia.

Pwamang JA (2009) The E-Waste Situation in Ghana.

Qingjie G, Jun D, Yunchuan X, et al (2008) Calculating Pollution Indices by Heavy Metals in Ecological Geochemistry Assessment and a Case Study in Parks of Beijing. Journal of China University of Geosciences 19:230–241. doi: 10.1016/S1002-0705(08)60042-4

Rademaker JH, Kleijn R, Yang Y (2013) Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling. Environ Sci Technol 47:10129–10136. doi: 10.1021/es305007w

Reck BK, Graedel TE (2012) Challenges in Metal Recycling. Science 337:690–695. doi: 10.1126/science.1217501

Riba I, DelValls TA, Forja JM, Gómez-Parra A (2002) Influence of the Aznalcóllar mining spill on the vertical distribution of heavy metals in sediments from the Guadalquivir estuary (SW Spain). Marine Pollution Bulletin 44:39–47. doi: 10.1016/S0025-326X(01)00171-0

Riederer AM, Adrian S, Kuehr R (2013) Assessing the Health Effects of Informal E-Waste Processing. Journal of Health and Pollution. doi: 10.5696/jhp.v3i4.61

Robertson GP, Klingensmith KM, Klug MJ, et al (1997) Soil resources, microbial activity, and primary production across an agricultural ecosystem. Ecological Applications 7:158–170. doi: 10.1890/1051-0761(1997)007[0158:SRMAAP]2.0.CO;2

SBC (1989) 1989 Basel Convention on Control of Transboundary Movements and Disposal of Hazardous Waste.

SBC (2011) Where are WEee in Africa? Findings from the Basel Convention e-waste Africa Programme. Secretariat of the Basel Convention, Châtelaine, Switzerland

Schluep M, Hagelueken C, Kuehr R, et al (2009) Recycling from E-Waste to Resources. UNEP & Step Initiative, Berlin, Germany

Schluep M, Müller E, Hilty LM, et al (2013) Insights from a decade of development cooperation in e-waste management. In: ICT for Sustainability: Proceedings of the First International Conference on Information and Communication Technologies for Sustainability. ETH Institutional Repository Zurich, Switzerland, pp 45–51

Seligson D (2013) E-waste Challenges and Opportunity.

Selin H, VanDeveer SD (2006) Raising Global Standards: Hazardous Substances and E-Waste Management in the European Union. Environment: Science and Policy for Sustainable Development 48:6–18. doi: 10.3200/ENVT.48.10.6-18

Sembiring E, Nitivattananon V (2010) Sustainable solid waste management toward an inclusive society: Integration of the informal sector. Resources, Conservation and Recycling 54:802–809. doi: 10.1016/j.resconrec.2009.12.010

Sepúlveda A, Schluep M, Renaud FG, et al (2010) A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India. Environmental Impact Assessment Review 30:28–41. doi: 10.1016/j.eiar.2009.04.001

Shi G, Chen Z, Xu S, et al (2008) Potentially toxic metal contamination of urban soils and roadside dust in Shanghai, China. Environmental Pollution 156:251–260. doi: 10.1016/j.envpol.2008.02.027

Shi J, Wang H, Xu J, et al (2007) Spatial distribution of heavy metals in soils: a case study of Changxing, China. Environ Geol 52:1–10. doi: 10.1007/s00254-006-0443-6

Shinkuma T, Huong NTM (2009) The flow of E-waste material in the Asian region and a reconsideration of international trade policies on E-waste. Environmental Impact Assessment Review 29:25–31. doi: 10.1016/j.eiar.2008.04.004

Sinha-Khetriwal D, Widmer R, Schluep M, et al (2006) Legislating e-waste management: progress from various countries. Environmental Law Network International 1:2.

Song Q, Wang Z, Li J, Duan H (2012) Sustainability evaluation of an e-waste treatment enterprise based on emergy analysis in China. Ecological Engineering 42:223–231. doi: 10.1016/j.ecoleng.2012.02.016

Spalvins E, Dubey B, Townsend T (2008) Impact of Electronic Waste Disposal on Lead Concentrations in Landfill Leachate. Environ Sci Technol 42:7452–7458. doi: 10.1021/es8009277

StEP Initiative (2014) One Globah Definition of E-waste.

StEP Initiative (2015) 2013/2014 Annual Global Report on Electrical Electronic Waste. United Nation University, Bonn

StEP Initiative (2013) StEP Launches Interactive World E-Waste Map - United Nations University. http://unu.edu/media-relations/releases/step-launches-interactive-world-e-waste-map.html#info. Accessed 21 May 2014

Sun Y, Zhou Q, Xie X, Liu R (2010) Spatial, sources and risk assessment of heavy metal contamination of urban soils in typical regions of Shenyang, China. Journal of Hazardous Materials 174:455–462. doi: 10.1016/j.jhazmat.2009.09.074

Taylor SR, McLennan SM (1985) The continental crust: its composition and evolution.

Tue NM, Sudaryanto A, Minh TB, et al (2010) Accumulation of polychlorinated biphenyls and brominated flame retardants in breast milk from women living in Vietnamese e-waste recycling sites. Science of The Total Environment 408:2155–2162. doi: 10.1016/j.scitotenv.2010.01.012

UNEP (2005) E-waste: The Hidden Side of IT Equipment’s Manufacturing and Use: Early Warnings on Emerging Environmental Threats. United Nations Environment Programme

UNEP (2006) Nairobi ministerial declaration on the environmentally sound management of electronic and electrical waste.

US Department of Energy (2011) Critical Materials Strategy.

USEPA (1996) Proposed Guidelines for Carcinogen Risk Assessment.

USEPA (1989) Risk Assessment Guidance for Superfund, Vol. I: Human Health Evaluation Manual. Office of Soild Waste and Emergency Response

Van de Klundert A, Lardinois I (1995) Community and private (formal and informal) sector involvement in municipal solid waste management in developing countries. pp 10–12

Van den Berg R (1995) Human exposure to soil contamination: a qualitative and quantitative analysis towards proposals for human toxicological intervention values. National Institute of Public Health and Environmental Protection (RIVM)

Veihe A (2002) The spatial variability of erodibility and its relation to soil types: a study from northern Ghana. Geoderma 106:101–120. doi: 10.1016/S0016-7061(01)00120-3

Wang F, Huisman J, Meskers CEM, et al (2012) The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Management 32:2134–2146. doi: 10.1016/j.wasman.2012.03.029

Warrick AW, Zhang R, Moody MM, Myers DE (1990) Kriging Versus Alternative Interpolators: Errors and Sensitivity to Model Inputs. In: Roth K, Jury WA, Flühler H, Parker J (eds) Field-Scale Water and Solute Flux in Soils. Birkhäuser Basel, pp 157–164

Wath SB, Dutt PS, Chakrabarti T (2011) E-waste scenario in India, its management and implications. Environ Monit Assess 172:249–262. doi: 10.1007/s10661-010-1331-9

Wenning R, Ingersoll C (2002) Executive summary of the SETAC Pellston workshop on use of sediment quality guidelines and related tools for the assessment of contaminated sediments.

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, et al (2005) Global perspectives on e-waste. Environmental Impact Assessment Review 25:436–458. doi: 10.1016/j.eiar.2005.04.001

Williams E, Kahhat R, Allenby B, et al (2008) Environmental, Social, and Economic Implications of Global Reuse and Recycling of Personal Computers. Environ Sci Technol 42:6446–6454. doi: 10.1021/es702255z

Wilson DC, Velis C, Cheeseman C (2006) Role of informal sector recycling in waste management in developing countries. Habitat International 30:797–808. doi: 10.1016/j.habitatint.2005.09.005

Wong CSC, Duzgoren-Aydin NS, Aydin A, Wong MH (2007a) Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. Environmental Pollution 148:62–72. doi: 10.1016/j.envpol.2006.11.006

Wong CSC, Wu SC, Duzgoren-Aydin NS, et al (2007b) Trace metal contamination of sediments in an e-waste processing village in China. Environmental Pollution 145:434–442. doi: 10.1016/j.envpol.2006.05.017

Xing GH, Chan JKY, Leung AOW, et al (2009) Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. Environment International 35:76–82. doi: 10.1016/j.envint.2008.07.025

Xing Y, Lu Y, Dawson RW, et al (2005) A spatial temporal assessment of pollution from PCBs in China. Chemosphere 60:731–739. doi:10.1016/j.chemosphere. 2005.05.001

Yu GB, Liu Y, Yu S, et al (2011) Inconsistency and comprehensiveness of risk assessments for heavy metals in urban surface sediments. Chemosphere 85:1080–1087. doi: 10.1016/j.chemosphere.2011.07.039

Zeng X, Li J, Stevels ALN, Liu L (2013) Perspective of electronic waste management in China based on a legislation comparison between China and the EU. Journal of Cleaner Production. doi: 10.1016/j.jclepro.2012.09.030

Zhao G, Wang Z, Dong MH, et al (2008) PBBs, PBDEs, and PCBs levels in hair of residents around e-waste disassembly sites in Zhejiang Province, China, and their potential sources. Science of The Total Environment 397:46–57. doi:10.1016/ j.scitotenv.2008.03.010

Zheng N, Liu J, Wang Q, Liang Z (2010) Health risk assessment of heavy metal exposure to street dust in the zinc smelting district, Northeast of China. Science of The Total Environment 408:726–733. doi: 10.1016/j.scitotenv.2009.10.075

APPENDIX

Appendix 1 – Questionnaire for Recyclers (Source: (Amoyaw-Osei et al. 2011, EMPA, Switzerland))

<table>
<tr><td>Date:</td><td>GPS Location:
Latitude: _ _ _ _ _ _ _ _ _ _ _
Longitude: _ _ _ _ _ _ _ _ _</td><td colspan="2">Interviewer:</td></tr>
<tr><td colspan="4">Interview Introduction</td></tr>
<tr><td colspan="4">Before the beginning of the interview, the interviewer should localize the person who is responsible for recycling operations of the company.

I am _ (name of Interviewer) coming from _ _ _ _ _ _ _ _ _ _. We are collecting data on e-waste generation and management in order to _ _ _ _ _ _ _ _ _ _. Can we ask you some questions about e-waste? Thank you for participating in our survey.</td></tr>
<tr><td colspan="4">General Information about work</td></tr>
<tr><td colspan="2">Address / City</td><td colspan="2"></td></tr>
<tr><td colspan="2">Year Business Started</td><td colspan="2">☐ 1-5 years ☐ 5-10 years ☐ Above 5 years</td></tr>
<tr><td colspan="2">Educational Status</td><td colspan="2">☐ Primary/ Basic ☐ SHS
☐ Tertiary ☐ None</td></tr>
<tr><td colspan="2">Hometown</td><td colspan="2"></td></tr>
<tr><td colspan="2">Which e-waste activities does the company carry out?</td><td colspan="2">☐ Collection ☐ Dismantling/Recycling
☐ Others, Specify: _ _ _ _ _ _ _ _ _ _ _ _ _ _</td></tr>
<tr><td colspan="2">Do you or does your company belong to any recognised or registered association in Ghana?</td><td colspan="2">☐ Yes ☐ No</td></tr>
<tr><td colspan="2">If yes what are some of the benefits as a member of the group?</td><td colspan="2">☐ Price Negotiation ☐ Welfare
☐ Access to Loans ☐ Others, Specify:</td></tr>
<tr><td colspan="2">What are some of the challenges in the association?</td><td colspan="2">☐ Payment of Dues ☐ Unity in the association
☐ Activities of free riders ☐ Others, Specify:_ _ _ _</td></tr>
</table>

Introducing Question	
What are some of the items that constitute waste of Electrical & Electronic Equipment?	
☐	☐
☐	☐
☐	☐

	1.0 Collection of Waste Electrical and Electronic Equipment	
1.1	By which strategies and channel does your company collect e-waste	☐House to House ☐Business to B ☐siness Municipal Collection Points ☐Others, Specify: _ ______
1.2	Which stakeholders are involved and what are their responsibilities?	
1.3	In terms of amounts, which one is the most important strategy or channel for collection?	☐House to House ☐ Business to Business ☐Municipal Collection Points
1.4	Do you cooperate with other companies/ authorities for collection purposes?	☐ Yes ☐No
1.5	If yes, which ones? (In what ways?) Details	
1.6	Which company transports the materials during collection?	☐Self-Rental Services ☐Haulage or logistic service providers ☐Others, Specify: _____________
1.7	What are some of the indications you focus on in collecting your e-waste materials?	☐ Valuable ☐Accessibility ☐ Ease of Dismantling ☐Workability ☐ Distance to Operating points ☐ Others, Specify: _____________
1.8	What are the main obstacles for a proper e-waste collection?	☐Lack of identity for the collectors ☐Lack of uniform pricing ☐ Conflict with other road users ☐Others, Specify: _____________

1.9	What suggestions will you give to improve on the collection of e-waste?	☐ Access to loans ☐ Municipal/Community collection points ☐ Improve transportation (Cost & Access) ☐ Others, Specify: _ _ _ _ _ _ _ _ _ _ _ _ _ _

	2.0 Recycling / treatment of Waste Electrical and Electronic Equipment (WEEE)
2.1	a) Which electrical and electronic products does your company (collect and) treat?
2.2	b) Does your company pay or charge for the treatment of the respective product? Or does it accept the product for free?
2.3	c) If yes: how much does your company pay per unit or kg of each product? (Average price)

a) Product	b) Pay/Charge	c) Price (Indicate Unit)
IT and telecommunications equipment (category 1)		
PCs* (central unit)	☐ Income ☐ Cost ☐ Free	
CRT monitors*	☐ Income ☐ Cost ☐ Free	
LCD monitors*	☐ Income ☐ Cost ☐ Free	
Laptops*	☐ Income ☐ Cost ☐ Free	
Mobile phones*	☐ Income ☐ Cost ☐ Free	
Landline phones*	☐ Income ☐ Cost ☐ Free	
Printers*	☐ Income ☐ Cost ☐ Free	
Copy machines*	☐ Income ☐ Cost ☐ Free	
Scanners*	☐ Income ☐ Cost ☐ Free	
Fax machines	☐ Income ☐ Cost ☐ Free	
Consumer equipment (category 2)		
TVs (CRT)*	☐ Income ☐ Cost ☐ Free	
TVs (flat panel)*	☐ Income ☐ Cost ☐ Free	
Radios*	☐ Income ☐ Cost ☐ Free	

Video projector*	☐Income ☐ Cost ☐ Free	
DVD players	☐Income ☐ Cost ☐ Free	
Cameras	☐Income ☐ Cost ☐ Free	
Fridges*	☐Income ☐ Cost ☐ Free	
Air conditioners*	☐Income ☐ Cost ☐ Free	
Fans*	☐Income ☐ Cost ☐ Free	

	3.0 Material fractions arising from WEEE
3.1	a) Which material fractions arise from your company's recycling activities?
3.2	b) What does your company do with each material fraction? (Treatment / destination)
3.3	c) Passing on the respective fraction to a further treatment, disposal, refining, etc.: is this associated with income or with cost for your company or does this happen for free? (please tick)
3.4	d) In case of income or cost: could you indicate an average price you get or pay

a) Material Fraction	b) Treatment (Indicate Company)	c) Income/Cost	d) Price (Unit)
Copper		☐Income ☐ Cost ☐ Free	
Motherboards		☐Income ☐ Cost ☐ Free	
Plastics		☐Income ☐ Cost ☐ Free	
Aluminium		☐Income ☐ Cost ☐ Free	
Steel		☐Income ☐ Cost ☐ Free	
Iron		☐Income ☐ Cost ☐ Free	
Glass		☐ Income ☐ Cost ☐ Free	
Batteries		☐Income ☐ Cost ☐Free	
Others, Specify			
		☐Income ☐ Cost ☐Free	
		☐Income ☐ Cost ☐ Free	
		☐Income ☐ Cost ☐ Free	

4.0 General questions about recycling/treatment of e-waste
4.1 Which processes does your company carry out? ☐Sorting of products ☐Manual Dismantling ☐Shredding ☐Cable stripping/ granulation ☐ Separation of (Shredded) fractions ☐ Burning (e.g. cables, cases) ☐ Leaching (e.g. printed wiring boards) ☐ Others, specify:
4.2 How many workers are engaged in the recycling operation?

	5.0 Environmental and Health Issues	
5.1	What environmental measures do you or does your company undertake to prevent the release of hazardous substances?	☐ Prevent Open Burning ☐ Prevent Oil Spillage ☐ Properly discarding non-valuable fraction (Landfill) ☐ Others, Specify:
5.2	Which health and safety measures are undertaken by the company?	☐ Provision of Personal Protection Equipment ☐ Safety Training and Guideline ☐ Regular Inspection and check ups ☐ Nothing ☐ Others, specify:
5.3	Which of the following sickness do you normally report at the health centre or hospital as a result of your work?	☐ Eye Irritation ☐ Skin Irritation ☐ Kidney Problems ☐ Fever ☐ Blood and Brain disorders ☐ Flu-like symptoms ☐Headaches ☐ Lung Cancers ☐ Wounds
5.5	How long has this symptom been with you?	☐ 1-3 years ☐ 3-6 years ☐ Over 6 years
5.5	How do you treat some of the health issues identified?	☐ Self-medication ☐ Herbal Medicine ☐ Health centres/Hospitals ☐Others, Specify

5.6	In your opinion, which appliances do you consider most dangerous to human health from a risk assessment point of view?	☐ Energy Saving Lamps ☐Mobile Phones ☐CE ☐ IT ☐ LHHA ☐ Cooling & Freezing
5.7	In your opinion, which substances do you consider most dangerous to human health from a risk assessment point of view?	☐PBDEs ☐PCBs ☐PCDD/Fs ☐PAHs ☐ PFOAs ☐ Lead ☐ Mercury ☐ Cadmium ☐Chromium ☐ Hexavalent ☐Heavy Metals ☐ Combustion Products ☐ Others

	6.0 Social Issues	
6.1	How are the people employed in the business, based on contract, apprenticeship or others?	☐ Contract ☐ Apprenticeship ☐ Others, Specify
6.2	If employment is based on contract what amount is paid per contract (average estimate)	☐ Below 20 Ghana cedis ☐ 20-50 Ghana cedis ☐ 50-100 Ghana cedis ☐ Above 100 Ghana cedis
6.3	Are the workers covered under social security?	☐ Yes ☐ No
6.4	Are there financial supports for medical treatment of workers in the course of duty?	☐ Yes ☐ No
6.5	Are there opportunities for workers to learn or update their skills?	☐ Yes ☐ No
6.6	If yes what are some of the opportunities?	

	7.0 General questions	
7.1	Apart from e-waste, which other materials are your company working with?	☐ scrap metals ☐ paper ☐ plastic ☐ automobiles
7.2	Is your company working on a formal basis or is it an informal company?	☐ formal ☐ informal
7.3	From your point of view, what are the main obstacles for a proper e-waste treatment?	
7.4	From your point of view, what should be done to facilitate e-waste management?	☐ Policy Direction ☐ Recycling facility ☐ Credit Facility ☐ Others, Specify:_ _ _ _ _ _ _ _ _ _ _
7.5	Are you satisfied with the current financing mechanisms of e-waste management?	☐ YES ☐ NO
7.6	If no: what should be improved?	☐ Fee ☐ Regulation ☐ Corporate responsibility (EPR), etc.)
	General remarks	

Interview closure
• Thank you for participating in this survey

Appendix 2a Stakeholders, their interest, influence and perceived risk in E-waste Management (EM)

Stakeholder	Category	Interest	Influence	Readiness	What e-waste management needs from them	Perceived risks	Group	Color Code
Producers	P	1	1	Have vast experience in implementing similar systems elsewhere	Financial, physical, legal and informational responsibilities	May not have incentives to invest in the system	Private	
Importers	P	2	2	Have good knowledge of the Ghana EEE market	To take up all the responsibilities in the absence of the original equipment manufacturers (OEMs)	They may use other means to avoid paying the e-waste levy	Mixed	
Assemblers	S	3	3	They assemble according to the needs of the market	In Ghana not categorized. But are generally required to channel their wastes into proper recycling	They may sell their wastes to informal recyclers	Mixed	
Private Consumers	S	2	2	Low awareness on e-waste issues	They are required to know where to dispose of their e-waste	They may dump their e-waste along with municipal solid wastes	Private	
Corporate Consumers	S	3	3	Large stock of end-of-life equipment	Channel their stockpile for environmentally friendly recyclers	They may manage their e-waste in an unsustainable manner	Mixed	
Formal Collectors	P	1	1	Have knowledge about the commercial value of e-waste	To improve their collection rates	Wastes will be managed unsustainably	Private	

Informal Collectors	P	1	1	They are aware of the risks and values involved in e-waste	To be formalized and organize collection	They will continue to send wastes to where they can make the most money	Private	
Repairers / Refurbishers	K	1	1	They are mostly first site of dumping	Generally required to channel their wastes into proper recycling, though not categorical currently	They dump e-waste in municipal landfill site	Private	
Formal Recyclers	P	1	1	Have knowledge of e-waste values and hazards	Follow environmental standards	Informal sector will have upper hand	Private	
Informal Recyclers	P	3	3	They see e-waste as source of livelihood	Stop environmentally hazardous way of managing e-wastes	They will continue with their dangerous activities	Private	
Ministry of Environment	P	3	3	Capacity to make and enforce policies	To make and enforce regulations	There will be no EM	Government	
Ministry of Local Governance	S	2	2	Knowledge about municipal waste management	They implement legislation at the local level	EM will not be implemented at the local level	Government	
Ministry of Trade	K	2	3	Knowledge about waste trade	To help regulate e-waste dumping	There will no coordinated effort to stop e-waste imports	Government	
Inhabitants of e-waste disposal Sites	P	1	2	Already suffering from the activities	May serve as watchdogs	May feel left out and may spark conflicts with operators	Private	

Ministry of Communications	S	2	2	Have knowledge of e-waste	Financial, physical, legal and informational responsibilities	May not have incentives to invest in the system	Government	
Ghana Standard Board	K	2	2	Have acquired vast experience in implementing similar systems elsewhere	To take up all the responsibilities in the absence of the Original equipment manufacturer (OEM)	They may use other means to avoid paying the e-waste levy	Government	

Appendix 2b: Graph Matrices of stakeholder Analysis

Stakeholder	**Label**	**In-Degree**	**Out-Degree**	**Betweenness Centrality**	**Closeness Centrality**	**Eigenvector Centrality**	**Clustering Coefficient**	**Type**
Producers	Prod	10	13	13.830	0.042	0.059	0.458	Formal
Importers	Imp	12	11	15.887	0.043	0.063	0.474	Mixed
Assemblers	Assem	9	5	5.205	0.036	0.048	0.591	Mixed
Private Consumers	PC	9	4	0.515	0.033	0.044	0.733	Informal
Corporate Consumers	CC	9	3	0.515	0.032	0.040	0.792	Formal
Formal Collectors	FC	9	13	8.992	0.040	0.057	0.505	Formal
Informal Collectors	IC	10	11	4.366	0.037	0.051	0.545	Informal
Ministry of Trade	MOT	10	8	7.945	0.034	0.043	0.536	Formal
Research Institutions	RI	11	19	24.430	0.048	0.067	0.424	Formal

Ghana Standard Board	GSB	7	7	4.385	0.034	0.043	0.591	Formal
Formal Recyclers	FR	13	20	25.459	0.048	0.072	0.421	Formal
Informal Recyclers	IR	13	20	25.459	0.048	0.072	0.421	Informal
Retailers	Ret	11	0	0.960	0.034	0.047	0.718	Informal
Wholesalers	WS	10	0	0.737	0.033	0.044	0.744	Formal
Refurbishers	Rfurb	10	12	2.132	0.036	0.052	0.568	Informal
Ministry of Communication	MCI	7	0	1.044	0.030	0.025	0.595	Formal
Ministry of Environment	MEIST	6	8	2.532	0.032	0.036	0.625	Formal
Ministry of Local Government	MLG	7	13	15.310	0.040	0.053	0.419	Formal
Ministry of Health	MOH	5	7	1.960	0.031	0.030	0.625	Formal
Inhabitants of e-waste disposal Sites	Residents	6	7	2.087	0.031	0.032	0.714	Informal
Downstream Marketers	DSM	2	5	0.250	0.029	0.022	0.800	Mixed

Appendix 2c: Parameters in stakeholder assessment

Primary (P): People directly affected by EM outcomes
Secondary (S): People not directly affected by EM outcomes but have an interest/influence on EM
Key (K): It is or could be an important player for EM success
Interest: Assessment of stakeholder interest on EM in Ghana (1=high, 2=medium, 3=low)
Influence: Assessment of stakeholder influence (power) on EM in Ghana (1=high, 2=medium, and 3=low)
Readiness: Assessment of stakeholder knowledge or experiences with EM in Ghana
What EM needs from these stakeholders?: What is or should be the stakeholder's contribution to EM
Perceived/attitude risk: The probable risk that the stakeholder poses to the sustainability of EM
Risk if they are not engaged: The resulting problems if the stakeholder is not engaged in EM process

Appendix 3: Results from Soil Analysis for Nine (9) heavy metals from AEPS

SN	Latitude	Longitude	Location/Site	Cr	Co	Ni	Cu	Zn	Cd	Ba	Hg	Pb
A1	807121.37	614385.63	Dismantling	53.20	10.80	ND	27.00	53.10	ND	120.60	ND	30.20
A2	807581.55	613958.03	Dismantling	67.80	16.00	ND	39.10	93.80	ND	205.00	ND	42.30
A3	807272.10	614593.86	Dismantling	109.50	26.30	0.60	76.30	262.20	ND	290.10	ND	65.40
A4	807188.07	614427.45	Dismantling	123.40	29.60	1.80	125.60	354.30	ND	339.70	ND	65.90
A5	807147.84	614412.10	Dismantling	128.90	33.20	2.10	208.10	498.70	ND	351.50	ND	161.70
A6	807719.63	614713.12	Dismantling	130.60	33.70	5.60	213.90	613.90	0.50	358.60	ND	228.80
A7	807442.61	614601.12	Dismantling	142.80	36.20	9.30	420.30	702.90	1.20	372.90	ND	230.40
A8	807393.02	614332.93	Dismantling	143.10	45.50	10.50	459.50	791.40	1.30	399.80	ND	268.90
A9	807327.07	614530.74	Dismantling	147.70	45.80	11.60	496.90	799.80	2.40	464.30	ND	354.90
A10	807509.29	614549.92	Dismantling	193.60	48.40	20.80	766.90	909.10	2.70	604.50	ND	392.30
A11	807348.15	614491.19	Dismantling	205.40	50.40	24.30	770.90	989.40	2.80	613.10	ND	512.50
A12	807508.29	614545.00	Dismantling	216.70	51.30	28.60	808.30	1062.00	3.10	635.90	ND	513.20
A13	807392.23	614408.58	Dismantling	219.30	54.80	30.60	852.00	1129.00	3.50	640.60	ND	573.20
A14	807507.52	614584.74	Dismantling	232.50	56.10	31.20	963.30	1378.00	3.70	648.50	ND	578.20
A15	807373.91	614447.26	Dismantling	234.10	56.30	31.50	1031.00	1458.00	3.80	648.60	0.70	650.30
A16	807400.54	614542.78	Dismantling	248.60	56.60	32.90	1245.00	1545.00	4.70	662.60	0.70	685.20
A17	807119.39	614428.94	Dismantling	262.00	60.10	35.00	1380.00	1552.00	4.90	742.10	0.80	724.90
A18	807326.86	614530.47	Dismantling	271.90	61.50	39.60	1445.00	1579.00	5.50	754.70	0.80	729.30
A19	808159.43	613905.66	Dismantling	274.60	62.00	40.70	1472.00	1618.00	5.50	757.00	0.80	751.50
A20	807508.88	614523.31	Dismantling	314.60	64.00	41.60	1539.00	1703.00	5.70	782.40	0.80	828.00
A21	807470.25	614550.85	Dismantling	325.60	65.80	42.40	1607.00	1727.00	6.00	793.10	0.90	829.50
A22	807491.25	614475.04	Dismantling	343.30	67.30	44.00	1667.00	1735.00	6.00	795.30	1.00	840.10

A23	807491.23	614475.02	Dismantling	439.90	68.20	47.40	1686.00	1741.00	6.90	855.20	1.10	843.10
A24	807211.02	614388.22	Dismantling	458.50	70.50	47.70	1757.00	1833.00	7.20	879.20	1.10	900.50
A25	807306.71	614559.25	Dismantling	464.30	71.30	50.30	1838.00	1833.00	7.60	883.80	1.20	948.10
A26	808092.66	613838.46	Dismantling	466.60	71.70	56.90	1857.00	1995.00	7.60	924.40	1.30	979.30
A27	807507.70	614585.25	Dismantling	486.30	73.60	57.80	2046.00	2061.00	9.30	940.30	1.40	1002.00
A28	807683.70	614678.98	Dismantling	486.30	76.80	60.90	2060.00	2283.00	10.20	964.80	1.80	1004.00
A29	807986.75	613734.04	Dismantling	505.80	76.90	65.40	2216.00	2298.00	10.30	969.00	1.90	1028.00
A30	807749.76	614750.89	Dismantling	508.00	83.20	66.20	2300.00	2456.00	10.80	970.60	1.90	1042.00
A31	807514.13	614569.47	Dismantling	545.70	88.00	66.70	2336.00	2853.00	11.60	985.50	2.10	1118.00
A32	807605.15	614593.88	Dismantling	679.80	90.30	67.00	2345.00	3216.00	12.90	1022.00	2.10	1189.00
A33	807656.80	614649.66	Dismantling	685.70	92.10	67.50	2682.00	3377.00	13.10	1074.00	2.20	1194.00
A34	807632.01	614612.47	Dismantling	716.50	94.60	71.90	2836.00	3608.00	13.80	1147.00	2.60	1269.00
A35	808214.99	613950.11	Dismantling	783.90	96.50	80.60	2881.00	3642.00	15.80	1178.00	3.20	1308.00
A36	807787.89	614806.03	Dismantling	896.90	99.00	95.20	3016.00	3654.00	17.30	1179.00	4.30	1407.00
A37	807594.13	614561.47	Dismantling	957.50	105.70	95.30	3231.00	3697.00	21.40	1222.00	5.40	1662.00
A38	807534.02	614495.19	Dismantling	1099.00	109.50	96.10	3289.00	3698.00	21.60	1313.00	6.20	2013.00
A39	807420.38	614472.93	Dismantling	1238.00	116.30	101.90	4138.00	5371.00	25.40	1469.00	7.20	2196.00
A40	807820.01	614872.78	Dismantling	1332.00	153.70	106.10	5615.00	5398.00	26.10	2635.00	9.90	2714.00
A41	807084.71	614379.52	Burning	439.20	95.05	85.00	18285.00	12907.50	26.50	1279.00	12.90	10280.00
A42	807302.59	614289.93	Burning	322.75	74.70	52.60	11260.00	9530.00	23.70	1034.00	9.70	9020.00
A43	807439.01	614275.67	Burning	271.55	69.50	48.60	10630.00	7333.00	20.25	1027.00	8.10	6832.00
A44	807420.51	614473.54	Burning	227.90	67.20	39.75	7526.00	5215.00	19.50	981.70	7.10	6830.00
A45	807408.47	614184.05	Burning	220.40	57.80	33.30	5791.00	4599.00	18.20	938.40	7.10	6468.00
A46	807121.37	614418.21	Burning	201.00	54.60	27.00	5252.50	3067.00	17.90	911.10	6.40	5814.00
A47	807430.92	614298.63	Burning	192.60	52.40	25.60	4282.58	2299.50	14.50	884.65	5.30	4891.00

A48	807427.48	614348.03	Burning	192.10	46.70	20.10	4143.00	1589.17	12.50	848.40	4.20	3656.50
A49	807276.12	614257.35	Burning	188.40	39.90	18.10	2945.00	1141.00	12.20	831.60	3.85	3114.00
A50	807272.04	614322.51	Burning	185.90	38.65	16.70	1823.50	1079.00	11.60	576.95	2.60	2280.00
A51	807251.68	614285.86	Burning	157.80	35.87	14.00	1690.00	736.50	8.20	558.00	2.30	1895.87
A52	807174.31	614373.41	Burning	149.70	35.10	12.50	1407.00	583.20	7.10	535.03	1.70	1471.00
A53	807237.43	614359.16	Burning	140.00	34.40	9.90	886.80	564.00	5.60	404.90	1.40	1050.00
A54	807121.19	614383.65	Burning	120.60	32.50	9.90	530.55	406.30	4.40	387.20	1.20	892.50
A55	807447.16	614157.58	Burning	114.80	31.35	9.80	386.80	402.60	4.00	385.30	1.10	389.50
A56	807247.61	614294.00	Burning	96.10	30.70	9.30	247.70	392.50	2.00	378.10	0.90	261.40
A57	807795.21	614748.82	Burning	89.40	27.80	8.00	205.10	386.50	1.10	350.10	0.00	236.90
A58	807353.11	614201.35	Burning	83.50	27.00	6.80	153.50	359.40	1.00	321.25	0.00	199.85
A59	807194.67	614312.33	Burning	80.80	25.90	5.20	132.50	261.20	0.80	293.20	0.00	137.35
A60	807443.09	614251.24	Burning	69.00	23.20	3.28	86.10	197.80	0.60	275.30	0.00	108.00
A61	807386.07	614259.39	Burning	58.60	19.60	3.20	72.20	158.20	0.50	270.50	0.00	81.20
A62	807706.05	614444.38	Commercial Area	732.10	35.40	12.20	256.00	821.00	1.40	973.70	1.00	352.50
A63	807485.87	614671.50	Commercial Area	316.40	34.10	10.20	256.00	546.70	1.20	677.40	0.90	312.90
A64	807435.60	614719.79	Commercial Area	241.70	33.80	8.50	213.60	517.60	0.90	518.20	0.90	295.50
A65	807706.12	614444.23	Commercial Area	238.70	30.60	5.90	155.50	458.50	0.80	490.20	0.00	206.00
A66	807541.43	614628.51	Commercial Area	91.80	27.10	2.20	154.60	420.80	0.50	477.90	0.00	152.70
A67	807460.07	614699.28	Commercial Area	86.40	23.80	1.10	128.50	232.40	0.50	403.40	0.00	127.10
A68	807505.71	614650.33	Commercial Area	75.60	21.80	ND	62.90	180.30	ND	390.50	0.00	94.80
A69	807664.96	614422.33	Commercial Area	49.60	19.40	ND	52.60	150.00	ND	281.80	0.00	65.50
A70	807652.81	614291.96	Eating Place	737.60	77.60	49.20	8254.00	2322.00	11.10	718.80	3.20	1441.00
A71	807424.75	614419.35	Eating Place	598.70	73.50	39.40	837.00	1344.00	2.70	688.40	1.20	500.00
A72	807675.21	614070.02	Eating Place	581.30	40.10	27.20	509.90	1225.00	2.20	671.60	1.10	281.30

A73	807158.08	614459.48	Eating Place	311.90	34.10	11.20	223.60	362.60	1.10	664.20	0.00	253.70
A74	807426.34	614556.27	Eating Place	284.20	21.50	1.40	192.30	276.20	0.50	587.30	0.00	174.70
A75	807452.53	614614.22	Eating Place	268.00	19.60	1.10	83.50	241.50	0.40	561.00	0.00	91.20
A76	807683.04	614398.52	Eating Place	168.90	16.40	1.00	66.90	240.80	ND	353.80	0.00	87.20
A77	808021.37	613660.74	Eating Place	53.70	16.30	ND	62.00	120.00	ND	173.00	0.00	74.60
A78	807033.81	614340.83	Farm	70.30	11.20	9.60	42.40	41.90	ND	226.30	0.00	52.10
A79	806909.74	614498.86	Farm	85.00	20.20	3.80	57.70	166.20	ND	287.90	0.00	74.50
A80	806907.56	614503.73	Farm	122.90	24.10	5.90	61.20	228.50	ND	308.20	0.00	87.00
A81	807295.76	614622.55	Farm	1007.00	30.80	1.60	82.70	285.60	ND	355.70	1.00	106.30
A82	807295.93	614622.41	Farm	310.90	32.40	3.50	213.10	633.90	ND	399.00	1.50	397.60
A83	807793.31	614190.15	Clinic	109.20	14.30	ND	39.40	181.10	ND	370.40	0.00	53.60
A84	808114.75	613697.11	Clinic	129.30	42.60	ND	42.00	259.90	ND	791.80	0.00	57.90
A85	808307.07	613899.31	Worship centre	121.30	11.80	ND	57.70	178.40	ND	374.00	0.00	64.30
A86	806948.29	614636.08	Worship centre	59.90	38.60	1.90	66.30	199.60	ND	671.70	0.60	67.80
A87	807626.39	614284.37	Worship centre	372.70	41.20	12.90	230.50	881.90	0.90	1306.00	0.70	218.90
A88	808224.93	613773.70	School	140.50	45.10	4.40	29.30	137.50	ND	269.40	0.00	48.40
A89	808326.12	613837.40	School	97.00	39.40	ND	65.80	448.80	0.50	519.30	1.10	174.20
A90	807909.38	614149.43	Market	40.10	16.10	ND	9.40	48.90	ND	133.30	ND	14.20
A91	807911.41	614269.57	Market	59.50	19.00	ND	39.70	142.90	ND	250.20	ND	45.00
A92	807753.89	614413.37	Market	87.20	23.60	0.70	42.60	168.00	ND	411.70	ND	45.70
A93	807176.34	614422.28	Market	93.20	24.90	1.70	58.30	181.80	ND	415.40	ND	75.40
A94	807744.97	614402.17	Market	97.00	25.10	2.40	78.80	229.40	ND	423.00	ND	77.70
A95	807798.00	614369.95	Market	111.70	29.00	5.00	93.10	319.20	ND	438.20	ND	90.90
A96	807186.52	614432.46	Market	163.70	30.10	7.40	110.00	341.30	ND	444.80	ND	113.40
A97	807958.25	614220.70	Market	302.50	34.90	13.70	176.60	696.50	1.00	653.90	ND	152.40

A98	807403.18	614674.81	Market	813.50	107.40	34.20	930.40	7897.00	6.10	778.80	1.40	865.30
A99	807640.64	614404.50	Residential	21.10	13.50	ND	38.30	194.50	ND	391.00	ND	48.10
A100	807895.12	614239.02	Residential	46.60	14.60	ND	41.60	226.20	ND	403.40	ND	57.80
A101	807683.36	614000.79	Residential	49.80	15.90	ND	59.00	227.60	ND	504.60	ND	58.40
A102	807903.27	614179.97	Residential	51.60	16.10	ND	59.10	236.90	ND	509.00	ND	61.00
A103	807601.91	614171.83	Residential	56.70	17.80	1.10	62.50	260.00	ND	542.70	ND	71.30
A104	807801.46	614155.54	Residential	59.40	19.40	2.10	64.40	260.60	ND	567.40	ND	86.40
A105	807595.80	614082.24	Residential	71.80	24.00	4.20	94.40	307.90	0.90	571.10	ND	89.40
A106	807937.91	613624.67	Residential	100.30	25.50	6.60	150.80	309.40	1.00	581.10	ND	111.90
A107	807638.60	614361.75	Residential	103.80	27.30	13.90	335.90	542.90	1.80	599.30	ND	149.50
A108	807474.97	614601.14	Residential	149.80	52.30	22.30	547.90	885.60	2.90	666.00	1.00	370.20
A109	807603.99	614164.24	Residential	171.90	72.00	34.00	1106.00	1181.00	3.70	717.50	1.60	567.50
A110	807469.60	614551.11	Residential	275.40	81.40	49.00	1198.70	1542.00	3.80	802.10	2.40	738.50
A111	807423.35	614368.69	Residential	291.70	94.20	56.70	2478.00	2063.00	4.90	825.00	2.80	879.90
A112	807491.22	614475.08	Residential	313.00	105.80	65.70	3271.00	2765.00	5.50	826.70	3.60	2488.00
A113	807409.80	614639.75	Residential	318.40	115.70	73.30	5656.00	3317.00	7.90	977.40	4.90	2656.00
A114	808257.98	613810.89	Residential	380.60	129.00	4003.00	6510.00	4407.00	9.60	1045.00	13.40	5903.00
A115	807351.59	614674.15	Recreation	102.00	25.90	7.40	140.30	75.30	0.60	213.70	ND	119.80
A116	807029.74	614682.92	Recreation	124.80	26.10	8.20	151.80	170.40	0.60	226.60	ND	153.10
A117	807420.78	614559.85	Recreation	160.10	27.90	9.40	218.40	183.20	0.70	271.10	ND	209.25
A118	807353.59	614600.32	Recreation	649.55	64.20	34.40	245.20	224.70	3.90	739.70	1.00	735.00
A119	807459.89	614603.86	Recreation	297.20	33.90	10.60	325.30	2540.00	1.50	377.20	0.40	286.40
A120	807423.56	614571.75	Recreation	366.90	34.20	13.60	343.50	526.50	1.70	439.10	0.40	447.60
A121	807459.67	614604.30	Recreation	480.10	45.20	15.60	365.50	569.90	2.20	505.70	0.70	536.60
A122	807434.67	614576.91	Recreation	511.00	55.30	19.80	905.25	701.70	2.60	157.20	0.80	609.40

A123	807353.31	614600.72	Recreation	60.50	8.80	1.20	44.10	781.55	ND	213.70	ND	36.80
A124	807845.08	614329.45	Roadside	53.00	16.60	ND	75.80	200.90	ND	445.70	ND	49.50
A125	807807.83	614356.19	Roadside	74.10	19.90	3.90	84.80	205.20	ND	455.70	ND	59.70
A126	807901.23	614255.31	Roadside	583.70	25.50	4.60	88.60	250.70	ND	474.20	0.50	122.50
A127	807691.72	614460.68	Roadside	604.20	28.60	5.60	120.00	251.60	ND	555.90	0.60	126.50
A128	807886.11	614850.05	Roadside	811.00	30.00	8.20	137.20	287.90	0.60	585.60	0.70	131.30
A129	807655.84	614504.11	Roadside	868.90	33.90	9.40	181.80	463.80	0.60	601.80	0.90	146.70
A130	807572.87	614574.50	Roadside	881.00	42.80	24.50	526.80	665.20	2.60	788.00	2.20	447.50
A131	807846.25	614287.89	Roadside	36.90	16.80	ND	31.70	111.20	ND	350.10	0.00	46.20
A132	807890.11	614297.68	Roadside	50.90	19.40	ND	35.60	149.80	ND	414.90	0.00	46.50

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