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MIGRATION AND DISPERSION OF HEAVY METAL CONTAMINANTS AT AGBOGBLOSHIE-AN ELECTRONIC WASTE RECYCLING SITE IN ACCRA.

BY

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OCTOBER, 2021

DECLARATION

I, Charles Christopher Asamoah hereby declare that apart from references to the works of others which have been duly acknowledged, this dissertation is the result of my independent work and has not been submitted in any institution for the award of any degree.

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DEDICATION

This thesis is dedicated to God and my family.

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Abstract

Introduction: In Ghana, the unregulated recycling practices of individuals, in particular informal recyclers, and the lack of a well-structured management policy or strategy have resulted in environmental contamination through the release of heavy metals from some unconventional methods of recycling into surface soils. As such, heavy metals tend to penetrate deeper soil profile (toward the water table) and also migrate from the source of generation to surrounding soils and other media such as water in the environment. **Objective:** We investigated the movement of heavy metals from the focal point sources of generation across environmental media (soil and water) and the contamination associated with the informal recycling of e-waste. **Methods:** The study was an analytical cross-sectional study involving laboratory analysis of heavy metals in water and soil samples from the Odaw river and the Agbogbloshie e-waste dumpsite and nearby areas. Pb, Cd, As, and Hg were measured in 76 soil samples and six water samples taken at twenty-meter intervals using a handheld global positioning system to locate sampling points. Metal levels were measured using Atomic Absorption Spectrophotometer. We evaluated the individual contributions of each heavy metal to the total soil contamination using environmental pollution indices such as contamination factor, degree of contamination (Cdeg), and pollution load index and compared levels in water to permissible limits. **Results:** Results from soil analysis showed higher levels of Pb, Cd, As, and Hg in surface soils (58.77, 342.26, 4.82, 3.76) and subsoils (56.16, 210.16, 3.16, 2.20) at the main working area of burning. However, concentrations of Pb, As, Cd and Hg in surface and subsoils across all sampling areas exceeded their WHO/FAO thresholds for agricultural soils indicating that e-waste activities had an impact. In increasing order, Hg>As>Cd>Pb contributed significantly to the overall contamination degree of the surface soil and subsoil across job tasks. High accumulations of Pb, Cd, As, and Hg was also observed in water samples collected from Odaw river with the levels surpassing their permissible limits. **Conclusion:** Findings showed that the studied heavy metals are ubiquitous within surface soil and subsoil at Agbogbloshie and the higher levels of these metals were reflected in the environmental risk indices, indicating soil contamination at Agbogblshie beyond sources of generation to adjacent soils (residential, recreational, farming and commercial areas) as well as surface water (Odaw river). The present study demonstrated that urgent measures are needed to minimize heavy metals contamination resulting from e-waste recycling activities in Agbogblsohie, Accra.

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LIST OF ABBREVIATIONS

ATSDR	**A**gency for Toxic Substances and Disease Registry
As	Arsenic
Br	Bromine
Cr	Chromium
Cu	Copper
ECOLAB	Ecological Laboratory
E-waste	Electronic waste
FAO	Food and Agriculture Organization
Fe	Iron
Hg	Mercury
LCD	Liquid crystal display
LEKMA	Ledzokuku Krowor Municipal Assembly
Mg/Kg	Milligram per kilogram
Mg/L	Milligram per litre
MSW	Municipal solid waste
Ni	Nickel
PAH	Polycyclic aromatic hydrocarbon
PBDEs	Polybrominated diphenyl ethers
PCDDs	Polychlorinated dibenzodioxins
Pb	Lead
SD	Standard deviation
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

CHAPTER 1

1.0 INTRODUCTION

1.1 Background of the study

The changing lifestyles of electrical electronic equipment consumers, as well as the ever-increasing demand for newer and more efficient technologies, are all contributing to the large volumes of electronic waste (e-waste) containing heavy metals globally (Yu, Williams, Ju, & Yang, 2010). Over the past years, heavy metals contamination has been extensively studied predominantly because of increasing recognition of their effects on the environment and human health. It is estimated that about ten million contaminated sites exist in the world and more than half of them have been contaminated with heavy metals (Khalid, 2017). In Ghana, Agbogbloshie epitomizes a site where heavy metal contamination in soil and water is believed to be widespread due to informal electronic waste (e-waste) recycling activities (Atiemo et al., 2012; Brigden et al., 2008), one of the main anthropogenic sources of concern for releases of metals into the environmental media (Gangwar et al., 2019). Unregulated e-waste processing usually recovers gold, copper, and other valuable metals by applying simple but highly polluting techniques such as melting and burning.

The use of these high polluting techniques certainly causes substantial heavy metals pollution in aquatic (Chama et al., 2014) and terrestrial ecosystems, as earlier investigators including Atiemo et al. (2012), Brigden et al. (2008), Caravanos et al. (2011), Otsuka et al. (2012), and Itai et al. (2014) have all confirmed the existence of heavy metals in Agbogbloshie soils. These researchers identified significant amounts of cadmium (Cd), lead (Pb), arsenic (As), copper (Cu), mercury (Hg), nickel (Ni), and zinc (Zn) in the soil and have linked the sources of these metals in the soil to the informal recycling of e-waste. Similarly, significant quantities of other toxic mixtures of organic compounds; including polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzofurans (PCDFs), polybrominated diphenyl ethers (PBDEs), and polychlorinated dibenzo-p dioxins (PCDDs) have also been observed in soil samples from Agbogbloshie (Wittsiepe et al., 2015).

However, despite the wide body of literature that has been dedicated to the study of heavy metal pollution in the soil at Agbogbloshie, earlier studies have mainly focused on surface soil contamination (0-20 cm soil depth) although an inquiry into the migration of heavy metals in the soil profile of contaminated sites in developing countries (including major hubs for informal recycling activities) have been proposed by researchers such as Gruszecka & Wdowin (2013) and Iwegbue et al. (2006) to assess possible contamination of the lower soil and groundwater table. As noted by Atiemo et al. (2012), Brigden et al. (2008), Caravanos et al. (2011), Otsuka et al. (2012), and Itai et al. (2014), the unceasing operations of informal e-waste workers leave behind heavy metals deposits in the soil. Against this backdrop, there is a likelihood of a significant amount of heavy metals leaching into the subsoil, neighbouring soil and water sources away from the hub of the e-waste recycling activities.

Indeed a study of the horizontal distribution and vertical mobility (bioavailability at different depths) of heavy metals in the soil offers a great opportunity to assess the risk of contaminants entering the surface as well as groundwater (Rajmohan et al., 2014), especially where high porosity subsoil underlies the field and where the water table is high up (Belkhiri, Tiri, & Mouni, 2018). Besides, subsoil supplies important nutrients and water to help plants grow (Frelih-Larsen et al., 2018). The accumulation of heavy metals in this layer makes them easily accessible to plants, particularly root vegetables such as carrot, onion, ginger, and garlic which have been reported to be grown in the vicinity (Fosu-Mensah et al., 2017).

It is worth noting that the behaviour of contaminants varies significantly in different media (Armah, Quansah, & Luginaah, 2014). Generally, water and air contaminants spread rapidly by diffusion in substantial amounts (Prasad, 2004) whereas the rate at which pollutants in soil media spread is dependent on the soil properties as well as the climatic conditions (Hamelink et al., 1994; Verkleji, 1993). This raises the question of the level of contamination in the soil profile, adjacent soil as well as available water media around Agbogbloshie away from the epicentre of the recycling activities.

Owing to the nature of heavy metal pollution in soil, some areas of Agbogbloshie or even the depth of the soil may be more contaminated than others, which in turn can contaminate other environmental media such as water (surface and groundwater) in the vicinity.

1.2 Problem statement

Naturally, the soil acts as a pollutant sink (Aqeel, Jamil, & Yusoff, 2014). However, soils themselves become a wellspring of pollutants above a certain threshold and are therefore unable to mop up these pollutants. These contaminants (including heavy metals) may leach into deeper subsoils, enter groundwater, and ultimately into drinking (where potable water pipe networks are superficial as in Accra) and marine water. Heavy metals present in water deteriorate the water quality which may consequently affect human health and aquatic life.

Most often than not, humans are exposed to heavy metals in the soil through drinking contaminated water as well as ingesting plant products that have accumulated substantial amounts of heavy metals. Previous studies on the soil around the Agbogbloshie e-waste site have so far focused primarily on surface soil contamination. However, deep-rooted vegetables such as okro, potatoes, carrots, and onions that absorb some nutrients from the subsoil have been reported to be grown around the vicinity for both commercial and non-commercial purposes (Fosu-Mensah et al., 2017). There is a possibility of passing heavy metals (Hg, As, Cd, and Pb) that the Agency for Toxic Substances and Disease Registry (ATSDR) lists among the "Top Ten Hazardous Substances" that are of concern to the environment and human health via the food chain. Additionally, large amounts of heavy metals in soil inhibit the growth of plants and therefore decrease productivity, posing a risk to food security.

1.3 Conceptual framework

As shown in Figure 1 below, manual e-waste (1) processing includes burning (2), dismantling (3), and sorting (4) to obtain precious metals like copper and gold (Akormedi et al., 2013). The electronic devices are crushed during the process of dismantling using manual tools such as hammers, spanners, and chisels (Akormedi et al., 2013). Agbogbloshie informal e-waste recycling operation releases significant amounts of toxic substances such as heavy metals into the soil, groundwater, and surface water such as rivers via leaching, atmospheric deposition, or erosion (5). These metals end up in vegetables grown around the site (6), the water table (7), and eventually into water sources near the site. On eating or drinking from these sources, humans are exposed to these metals (9). In addition to this, humans are exposed to these metals through dermal contact. Exposure to these metals leaves harmful human health impacts (10).

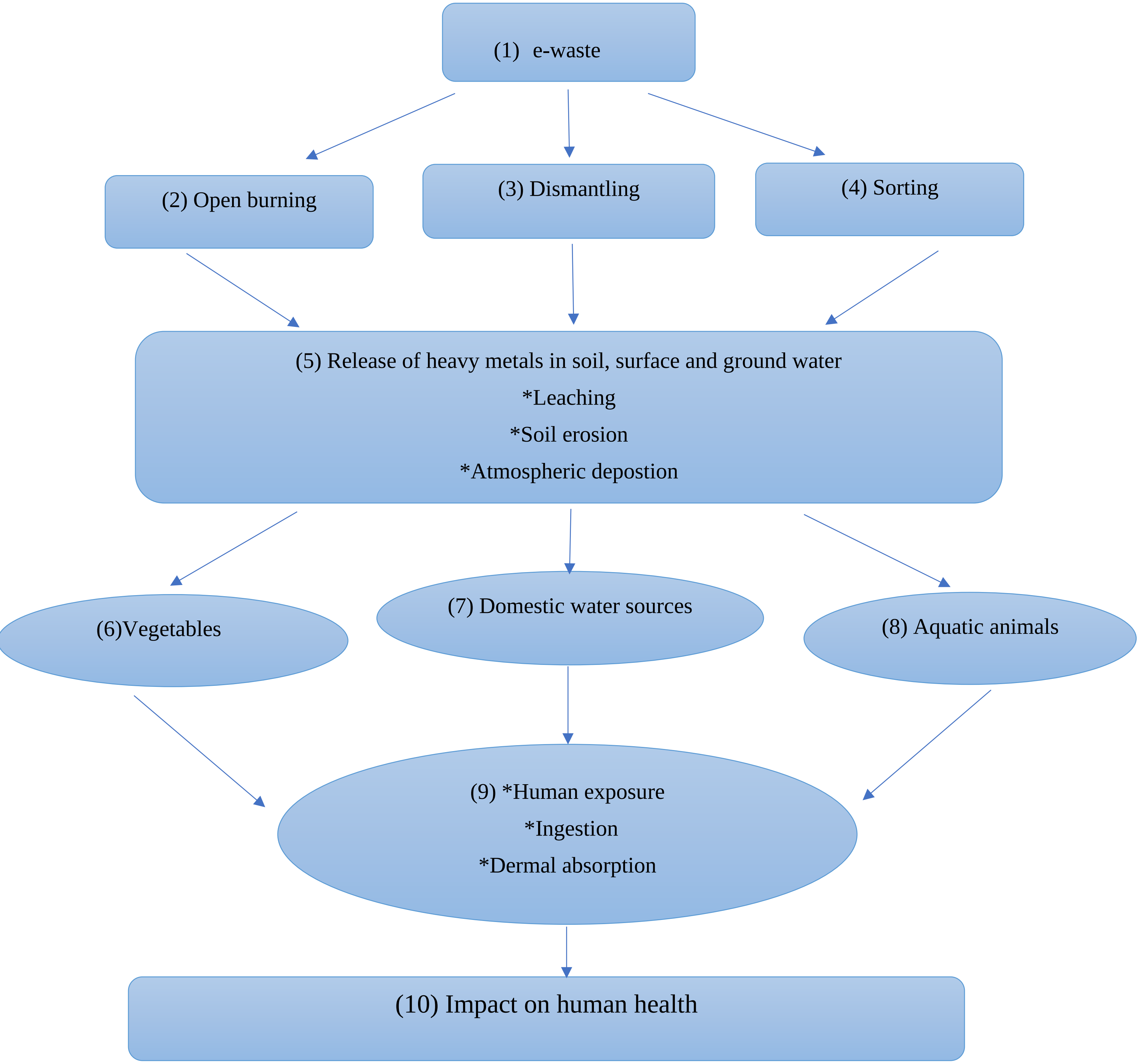

Figure 1.1: Conceptual framework showing the relationship between e-waste recycling and humans' exposure to heavy metals through soil and water contamination.

1.4 Justification of the study

Soil and water contamination impact food security. They undermine food security by disrupting plant metabolism and thereby decreasing crop yields, as well as making crops unsafe for consumption, hence making environmental media pollution and food safety two important issues. This study is particularly relevant since there is increasing knowledge about how adequate consumption of vegetables, fruits, and fish as an integral component of human nutrition can boost the immune system. However, in Accra, all these products are harvested from soil and water media around Agbogbloshie, which means that there may be possible risks in product safety and hence individuals may be at risk of heavy metals exposure indirectly. Furthermore, the rapid growth in population at Agbogbloshie and its surroundings call for the proper conservation of soil and water for sustainability. Therefore, it is of utmost importance to conduct investigations on the levels and extent of heavy metal contamination in these media for informed decisions on the approach to contamination reduction, reducing human vulnerability, and protecting the public from heavy metals exposure risk.

1.5 Research questions:

1. To what depth and extent can heavy metals migrate both vertically and horizontally from surface soils heavy metals contamination?
2. Starting from the epicentre of recycling activities, what are the amounts of metals in soils and water collected at various depths and across space?
3. What are the levels of variation of these contaminants at various depths and across space?

1.6 Study objectives

1.6.1 General objectives

The main objective of the study was to investigate the movement of heavy metals from the focal point sources of generation across environmental media (soil and water) and contamination associated with the informal recycling of e-waste.

1.6.2 Specific objectives

1. Collect soil and water samples at different depths and distances at and/or from the epicentre of e-waste recycling activities
2. Measure levels of heavy metals in the soils and water collected at different depths (top and subsoil) and across space starting from the epicentre of recycling activities.
3. Compare the concentrations at different distances from the epicentre.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

Electronics are a growingly large part of everyday life. In this regard, many electronic devices are being produced every year around the globe. According to Baldé et al. (2017), an approximation of 65 million tons of electronic waste (e-waste) was created around the globe in 2017. However, the financial burden in dismantling them makes developing countries such as Ghana, a hub for e-waste (Sthiannopkao & Wong, 2013). However, there is limited recycling technology for disposal and safe management in these developing countries (Akormedi, Asampong, & Fobil, 2013). Here, e-waste is primarily processed using high-polluting techniques. Indeed, It is worth noting that e-waste contains concomitants that are released during the recycling exercise (Heacock et al., 2018).

Recycling e-waste in an informal manner brews toxic substance which leaves negative footprints on the environment. These substances may be heavy metals, chemicals released from plastics, or brominated flame retardants. Significant levels of these contaminants may enter the soil, water, and air sources near recycling sites and these pose dangerous health threats to humans. Several studies have identified concentrations of chemical contaminants in soil and water that are greater than their accepted maximum levels and the effect they have on these media. At the Agbogbloshie e-waste processing site, the heavy metal burden has been established for soil and water (Leung et., 2008; Lu et al., 2009; Spalvins et al., 2008).

In fact, several pieces of literature exist on heavy metal pollution in the soil at Agbogbloshie. Yet a dearth of knowledge still existed as earlier researchers did not explore deeper soils to determine if heavy metals that spread over the surface soil accumulated only in the upper strata and did not leach into deeper soils. Hence, this work was intended to bridge that gap in information. And thus, this work was aimed at determining the extent of contamination of these metals from pollution sources to adjacent soil and available surface water Odaw river) as well as groundwater.

2.2 Heavy metals

"Heavy metals" are natural elements distinguished by their rather high density and high atomic mass. A density of at least $5gcm^3$ is widely used to describe and differentiate a heavy metal from other, "normal" metals (Koller & Saleh, 2018). Added to this, Koller & Saleh (2018) mentioned that, heavy metals usually occur at relatively low concentrations, and can be found all over the earth's crust. While heavy metals are found naturally in the earth's crust, most environmental pollution and human exposure to these metals are the results of human-induced activities (He et al., 2005). Tchounwou et al. (2012) also mentioned metal corrosion, atmospheric deposition, soil erosion of metal ions, leaching, re-suspension of sediments, and heavy metal evaporation from water to the soil, surface, and groundwater as ways through which environmental contamination with heavy metals can occur.

Heavy metals are important contaminants to the environment, and their toxicity is a major problem for ecological, developmental, nutritional, and environmental processes (Goyer, 2001; Wang & Shi, 2001). Bhat et al. (2017) pointed out that there are thirty-five metals of concern with regards to occupational and residential exposure, the majority of which belong to the category of heavy metals (arsenic, bismuth, antimony, cerium, cadmium, chromium, cobalt, copper, gold, gallium, iron, manganese, lead, mercury, nickel, platinum, silver, tellurium, thallium, tin, uranium, vanadium, and zinc) are commonly found in the environment and food. These according to Guo et al. (2013) makes them significant to consider because they are non-biodegradable and have a long biological half-life.

Compared with other types of exposure such as inhalation and dermal contact, food intake has been identified as the main route of human exposure to heavy metals (Monferran et al., 2016; Zhuang, et al., 2009). When the body does not metabolize heavy metals, they are toxic and accumulate in soft tissues when they enter the human body in the course of taking in food, water, or air. According to Wu et al. (2016), in small quantities, these metals are necessary for the maintenance of good health, but in larger quantities, they can become toxic or dangerous to human health. In the current scenario, As, Cd, Cu, Pb, and Hg are ranked among the list of priority metals because of their high degree of toxicity (ASTDR, 2019).

2.5 Characteristics of heavy metals studied

2.5.1 Lead

Research has shown that Lead (Pb) is a threat to the survival of living organisms because it occurs in every part of the environment. Pb is a toxic metal found naturally in the crust of the earth. Lead can be found naturally in the soil but mostly at low concentrations. Pb exposure is predicted to represent 0.6% of the global morbidity and mortality, with the greatest burden in developing countries (WHO, 2010). In fact, at low concentrations, Pb in humans can cause learning disabilities in children. The WHO (2010), also highlighted that adults exposed to Pb may also be at risk of reduced reaction time, nausea, insomnia, memory loss, anorexia, as well as joint weakness.

In line with the increased industrialization of the world, the Pb content in the environment has increased (Manahan, 2002). However, Pb does not travel in larger quantities in the soil (Fahr et al., 2013). Hence the leaching of inorganic Pb compounds and elemental Pb into groundwater under normal conditions is not prolific (UNEP, 2010). Research has shown that elevated Pb levels are more likely to be found in leafy vegetables and root crops (Alexander & Ubandoma, 2014). According to Fahr et al. (2013), plants usually do not absorb Pb, yet in agricultural soils with elevated Pb concentrations, there is a tendency for plants to take up some quantity of the metals. Pb poisoning or death may result from the accumulation of lead in the body's organs (WHO, 2017).

The buildup of Pb in the human body inhibits the transport of oxygen to human body cells (Bradl 2005). This is because lead can obstruct haemoglobin synthesis which is necessary for oxygen transport by hindering the actions of the two enzymes involved in its production, this occurrence according to Bradl (2005) progresses to anaemia. The principal pathways of Pb exposure are through inhalation and ingestion and the consequence of these processes are the same (Jaishankar et al., 2014).

2.5.2 Mercury

Naturally, mercury (Hg) is present in the environment, but while this is a naturally occurring substance, it does not make it harmless. Metallic mercury is a shiny silver-white, odourless liquid that becomes colourless and odourless when heated (Jaishankar et al., 2014). These are heavy metals with a history of industrial and personal use and also with a record of adverse human health effects (ATSDR, 1999). In the short term, contact with high amounts of metallic Hg vapours can cause nausea, skin rashes, diarrhoea, increased blood pressure, lung damage as well as irritation of the eye. In the long-term, individuals experience dizziness, weakness, loss of self-control, loss of memory, numbness and tingling, nervousness, tremors, pain in the limbs, and loss of peripheral vision (Lokeshappa et al., 2012).

2.5.3 Arsenic

These metals exist plentifully in rocks of the earth. Anthropogenic sources which include: mining, smelting, coal-fired power plants and pesticide applications are the major ways arsenic contaminates environmental media (air, soil, and water). Arsenic occurs in both organic or inorganic forms with the inorganic type generally considered to be the most harmful (E.P.A., 1997). Arsenic containing compounds can stick to soil and percolate into deeper soil profile. It does not have beneficial human metabolic functions. Arsenic is deemed as one that causes cancer. Even at small quantities of exposure, its negative effects on human cells are gross. It can cause nausea and vomiting at low contact levels, abdominal pains, and reduced white blood cell production and red blood cells. The surfacing of corns on palm soles as well as the darkening of the skin are major long-term effects of Arsenic exposure.

Soil's dynamic and complex nature allows it to function as a habitat for flora, animals, microorganisms, and humans. Contaminated soils pose a threat to human and environmental health as they cause chemical contamination of groundwater as well as the food chain (Hund-Rinke & Kördel, 2003). Arsenic can be used in computer chips, circuit boards, and LCDs. The Arsenic in electronic waste disposed of normally travels through soil slowly. According to Hund-Rinke & Kördel (2003), the composition of groundwater and soil is influenced by the contaminants that leach into the soil.

2.5.4 Cadmium

Eisler (1988) and Nordberg (2004) showed that Cadmium (Cd) plays no critical role in human metabolism. The first Cd-related effect on human health was the damage to Cd exposed workers' lungs, published in 1938 (Nordberg, 2004). A few years later, as a result of Cd exposure, pathological bone fractures and severe pain called Itai-Itai disease occurred in Toyama Japan during World War II (Nordberg, 2004). Cadmium remains an important metal in the industry. Cd is a metal essential for industrial purposes. Cadmium is extracted when other metals are being made. Such metals include copper and zinc.

Apart from its value in the industrial environment, it is also used in home-made products such as pigments, metal coatings batteries, plastics, and some metal alloys (Keith et al., 2008). Cd-containing materials are rarely recycled but instead discarded in conjunction with household waste, thereby contaminating the environment, particularly when the waste is incinerated (Järup, 2003). Low concentrations can also be found in food and e-waste (Wang & Du, 2013). The introduction of agricultural inputs such as fertilizers and pesticides, atmospheric deposition, or effluent from industries raise the overall Cd content in soils. Even at low concentrations, Cd is toxic to the life of all living organisms (Eisler, 1988; Keith et al. 2008; Nordberg 2004). Ingestion of Cd contaminated foods is the common source of toxicity to Cd in humans (Keith et al., 2008).

2.3 Heavy metals in water

The importance of water supplies in meeting the human, animal, and industrial water needs indicate the critical need to protect them from pollution. Perhaps the most important resources are water supplies. Biological and chemical pollutants including heavy metals reach water supplies when urban, commercial, and agricultural waste enters the water. In most cases, their sources in the aquatic environment are largely anthropogenic rather than natural sources (Binning and Baird, 2001). Mohiuddin et al. (2011) mentioned that heavy metals present as a contaminant in water are an indicator of anthropogenic behaviours that can be linked to practices such as improper disposal of heavy metal-containing e-waste. It is noteworthy that some of these heavy metals are essential (Arif et al., 2016).

However, although some of these heavy metals serve as important nutrients, their high quantities in the food chain can lead to toxicity and consequently threaten aquatic environments and their users (Prabu, 2009; Kane & Lazo, 2012). The essential metals needed for important processes in living organisms lie in the narrow "range" between their essentiality and toxicity (Fatoki et al., 2002), and thus require constant monitoring (Merian and Clarkson, 1991). Consequently, studying the entry routes, impact, and pollutant control in rivers has always been one of the environmental scientists ' areas of interest in recent times (Shanbehzadeh et al., 2014). The accumulation of heavy metals in an aquatic ecosystem has significant human and environmental implications.

In a study conducted by Brigden et al. (2008) to assess disposal and e-waste recycling sites contamination in Koforidua and Accra, Ghana, heavy metal concentrations in the Odaw River (located in Accra) were reported to be significantly higher than acceptable levels. Likewise, Asante et al. (2012) reported significant levels of heavy metals in the Odaw river. In addition to this, Chama et al. (2014) determined the concentration of trace metals that originate from the filth discharged, including both solid and excreted waste into the Odaw river, and also confirmed the presence of Fe, Cu, Pb, Cd, Cr, and Ni from sediment collected from the Odaw river. Heavy metals contaminated rivers can have an impact on the aquatic environment's ecological equilibrium and can reduce the abundance of aquatic species as the level of pollution increases (Ayandiran et al., 2010). Khayatzadeh & Abbasi (2010) stated that, at the population level, heavy metals in contaminated rivers may also impact fish species.

While previous studies (Brigden et al., 2008; Asante et al., 2012; Chama et al., 2014) confirmed the existence of heavy metals in the Odaw river (especially midstream), there were concerns about the pollution of the entire Odaw river and its estuary, as well as the Korle Lagoon due to its proximity to the Agbogbloshie disposal site. The proximity, combined with the incessant floods occurring in the city, increases the probability of e-waste being distributed to the different parts of the river (upstream, midstream, and downstream) and thus endangering the human and different aquatic life.

Against this backdrop, this study sought to investigate heavy metals and the extent of their distribution in the various parts of the Odaw river to ascertain if there were differences in the heavy metal components in the upstream, midstream, and downstream sections in hopes to bridge the gap in knowledge as to whether the composition of the heavy metal in the midstream was the result of metals being transported from the upstream or if the downstream composition of heavy metals was the product of metals being deposited at the midstream or perhaps these heavy metals being accumulated in the water were independent of the different sections (upstream, midstream, downstream) of the river.

2.4 Emission of heavy metals in the soil

Generally, heavy metals occur in trace amounts in the soil (Srinivasarao et al., 2014). That is, the normal concentrations of heavy metals in agricultural soils resulting from parent materials are not sufficient to negatively affect human health. According to Guo et al. (2013), anthropogenic sources including smelting, informal e-waste recycling, industrial effluent, vehicle emissions, mining, sewage sludge, and agro-chemical can significantly increase quantities of heavy metals in agricultural soils. An alarming trend around the world is the increasing number of reports on heavy metals toxicity in soils. Over the last decades, a growing interest in the knowledge of heavy metal levels in soils has been fueled by the accumulation and persistence of heavy metals on topsoil (0-20 cm), making them potentially key indicators of contamination in the environment (Burt et al., 2014).

In light of the keen interest in heavy metal accumulation in soils, scientists have dedicated resources to the study of this phenomenon. Field experiments to investigate heavy metal emissions in soil have been performed in a great number of studies. To mention a few, Perveen et al. (2017) analyzed soil samples obtained from an industrial area close to Swan River in Islamabad, Pakistan to examine heavy metals concentration and documented elevated amounts of Ni, Pb, Zn, Cd, and Cu in the soil. In Cleveland, USA, heavy metal pollution in the soil was addressed by sampling in the area of an abandoned and underutilized industry and nearly all sites had high concentrations of Fe, Pb, Cd, Cr except Cu and Ni (Jennings et al., 2002).

In Asia, Jeon et al. (2008) obtained soil samples from a rolling stock workshop, located in the central part of Seoul, Korea to analyze the levels of the heavy metal in the soil and reported substantial levels of Pb, Cu, and Cd with Pb and Cu exceeding the required limit. Likewise, Yang et al. (2016) recorded significantly high amounts of Pb and Zn although substantial levels of Cr, Cu, and Cd were also found in surface soil collected from the Qingshan district of Wuhan. Jamal et al. (2019) also recorded concentrations of heavy metals in the decreasing order of Pb, Zn, Cd, Cu, and Ni after analyzing the distribution of heavy metals in soil and evaluating the health risk of these metals around zinc and lead plants at a smelting plant in Zanjan, Iran.

African countries are no exception to this phenomenon. In Nigeria, a study by Edogbo et al. (2020) on soils sampled around Challawa industrial area, Kano State recorded lower levels of Pb with Cd and Cr in higher amounts. Maas et al. (2010) also recorded higher levels of Cr and Cd in urban, suburban, and agricultural soils collected in Algeria. Ghana is no different as a large number of research conducted on the toxicity of metals in different soils from different regions have also revealed higher heavy metal levels. Darko et al. (2019) recorded elevated levels of As, Cr, Ni, and Zn in topsoil samples from the Gbani mining community in the upper east region of Ghana.

Similarly, elevated quantities of Cr, Zn, Cd, Cu, and Pb were reported by Frimpong & Koranteng (2019) in their bid to determine the degree to which populations may be exposed to the health risk of surface soils heavy metals from fifty-six public parks selected from seven metropolitan cities in southern Ghana. These, including studies on soil samples collected from Agbogbloshie, a major hub for informal e-waste recycling activities in Ghana have all reported significant levels of toxic heavy metals.

In assessing heavy metal levels in soil at Agbogbloshie, Atiemo et al. (2012) collected surface dust from various locations in and around the vicinity and recorded elevated concentrations of Zn, Cu, Pb, and Cd. Likewise, Otsuka et al. (2012) also reported Cu, Zn, Pb, Sn in very high quantities although Br, Hg, and As were relatively lower in concentrations. Besides that, the existence of heavy metals in the soil at Agbogbloshie has also been confirmed by Itai et al. (2014), Caravanos et al. (2011), and Brigden et al. (2008) after examining the distribution of heavy metals in soils obtained from the area.

However, while surface contamination with heavy metals is used as an indicator of environmental contamination (Rajmohan et al., 2014), many researchers have recognized the relevance of studying subsoil contamination with heavy metals (Gruszecka & Wdowin 2013; Iwegbue et al. 2006). And this is because on reaching the soil, heavy metals and metalloids are subjected to various processes. These include sorption, precipitation, plant uptake, leaching, and volatilization (Garbisu & Alkorta, 1997; Garbisu & Alkorta, 2003). The quality of groundwater especially, the very shallow ones are threatened when heavy metals leach into deeper horizons of the soil (Iwegbue et al., 2006). In addition to this, plants with deep roots absorb some nutrients from this depth (Shaheen & Iqbal, 2018), yet the amount of heavy metal accumulated in the subsoil, as well as the extent of spread from the source of pollution to adjacent surface soil, had not been further investigated at Agbogbloshie. This study, therefore, sought to build on earlier studies done by Atiemo et al. (2012), Otsuka et al. (2012), Brigden et al. (2008), Caravanos et al. (2011), and Itai et al. (2014) who have in the past conducted research on heavy metal accumulation in surface soil at pollution sources and have confirmed the existence of heavy metals and other pollutants in substantial amounts at Agbogbloshie but had not investigated the extent of the contamination from these pollution sources both vertically and horizontally.

2.6 Heavy metals impact on soil

Heavy metal contamination contributes not only to adverse effects on different plant quality and yield parameters but also to changes in the size, structure, and function of the microbial community (Yao et al., 2003; Ashraf & Ali, 2007). The biodiversity of soil microbes and their activities play an essential part in recycling plant nutrients, maintaining soil structure, detoxifying harmful chemicals, as well as controlling plant pests and plant growth communities, hence making them important indicators of soil quality (Singh & Kalamdhad, 2011). Heavy metals are therefore regarded as one of the key causes of soil contamination (Karaca et al., 2010).

It is noteworthy that pH, clay content, and organic matter composition of soil have a significant effect on the magnitude of metal impacts on biological and biochemical materials (Speir et al., 1999). Huang et al. (2009) also mentioned that indirectly, heavy metals influence enzymatic activities in soil by altering the microbial population that synthesizes enzymes (Shun et al., 2009). Specifically, in the soil, heavy metals if present at sufficiently high concentrations, reduces the size of microbial populations, destroy their community composition, and therefore reduce their activity (Kandeler et al., 2000; Chander et al., 2001; Wang et al., 2009).

Karaca et al. (2010) pointed out that owing to the variations in soil enzymes and their chemical affinities, the enzyme activities are affected by different metals in various ways. For example, Singh & Kalamdhad (2011) noted that Cd is far more detrimental to enzymes than Pb due to its greater mobility and lower affinity to colloids in the soil. And thus specific soil enzymes have a specific sensitivity to heavy metals. Belkhiri et al. (2018) noted that groundwater is the main natural water resource for both drinking and agricultural purposes, however, with increasing concentrations in the environment and decreasing the capacity of soils to retain heavy metals, they leak into groundwater and soil solution.

Heavy metal contamination of the soil can present a risk to the ecosystem by contaminating groundwater, reducing food quality (safety and marketability) through phytotoxicity, reducing land usability for agricultural production, causing food insecurity and land tenure problems (McLaughlin et al., 2000; Ling et al., 2007).

2.7 The effect of heavy metals on water

Metals are readily dissolved in water and eventually consumed by marine species such as fishes and invertebrates, which have a broad variety of biological effects on them, ranging from important to lethal (Gheorghe et al., 2017). Even though some metals are necessary for living organisms at low concentrations, at higher concentrations, they may induce toxic effects that disrupt the growth, metabolism, or reproduction of organisms, with implications for the entire trophic chain including humans (Stankovic et al, 2014). Heavy metals released into receiving waters may result in several physical, chemical, and biological responses.

Density, diversity, community structure, and species composition of populations can change depending on the environmental conditions (Moore & Ramamoorthy, 1984). Heavy metals are not susceptible to microbial degradation and hence persist in the aquatic environments indefinitely (Woo et al., 2009). Moreover, the pollution of a waterbody with heavy metals can have detrimental effects on the aquatic environment's ecological balance and the variety of aquatic species is reduced by the magnitude of the pollution (Ayandiran et al., 2010). According to Singh & Kalamdhad (2011), heavy metals introduced into aquatic environments are bound to particulate matter, which gradually settles and dissolves into sediments.

Consequently, surface sediment is the most important reservoir or sink of metals and other pollutants in aquatic environments. Peng et al. (2008) mentioned that sediment-bound pollutants may be absorbed by macrophytes and other organisms. Gurrieri (2010) also reported that a large proportion of the heavy metals introduced into the aquatic environment eventually settle into bottom sediments, hence environmental degradation by heavy metals can occur in sections of the water where the water quality criteria are not exceeded. In addition to this, organisms in or near the sediments are adversely affected as a result.

The structure of the diatom community can be influenced by elevated levels of micropollutants, and particularly by heavy metals released into aquatic environments (De Jonge et al., 2008). When an aquatic organism accumulates heavy metals, they can be passed into the upper layers of the food chain. At the top of the food chain, carnivores including humans, obtain most of their heavy metal burden from the aquatic environment through fishes (Ayandiran et al., 2010). Fish is a product of possible public health concern as it can be polluted with a variety of non-degradable environmental contaminants, including heavy metals (Azzaz et al., 2018). Consuming fish with high metal levels is a concern, as chronic exposure to heavy metals can cause health problems.

2.8 Implications of heavy metals on human health

Heavy metals, despite their differences of origin, follow general biogeochemical cycles after entering the environment, although their transport, residence time, and fate vary from one environmental media to another (Kabata-Pendias, 2011). Notwithstanding, the level of heavy metals in soil and water continues to exist long after they have been injected into them through anthropogenic influence. Heavy metal contamination of these media poses risks and hazards for the ecosystem and humans (Järup, 2003; Gu, Gao, & Lin, 2016). Although a few heavy metals are essential for life, toxicity in humans, plants and animals can be triggered by absorption that exceeds recommended thresholds (Chauhan & Chauhan, 2014). Heavy metal contamination in soils is of concern to researchers and regulatory agencies because most metals have negative health effects.

Several pieces of literature have been published with respect to humans' exposure to heavy metals using biomarkers of exposure. In a research conducted to evaluate exposure among recycling workers and office workers at three e-waste recycling plants in Sweden to some potentially toxic metals, Julander et al. (2014) reported that the concentrations of Cr, Co, In, Pb, and Hg in the plasma, whole blood, urine, and air filters were significantly higher among recycling workers as compared to office workers. In Ghana, a study by Caravanos et al. (2011) found elevated levels of Pb, Cu, Al, Fe, and Zn in air samples collected from workers at the Agbogblsohie e-waste site.

Asante et al. (2012) also recorded significantly high amounts of Pb, As, Fe, and Sb in the urine of e-waste recycling workers at the site. Likewise, Srigboh et al. (2016) observed that the blood cadmium and lead levels in male and female workers at Agbogbloshie were higher than the U.S. CDC/NIOSH reference level whiles levels of urinary arsenic were also higher as compared to the U.S ATSDR value in research to characterize exposure to some essential and toxic elements in the urine and blood of male and female workers at Agbogblsohie. Lente et al. (2014) mentioned that ingestion, inhalation, and dermal absorption are the principal pathways by which heavy metals enter the human body.

On entering the body, heavy metals gradually build up over some time in the body and consequently leave negative footprints on the individual's health. The toxicity of heavy metals can be either acute or chronic (Azeh et al., 2019). Potential effects from heavy metal contaminants differ according to the type and nature of the metal, timing of exposure, frequency, length of exposure, and exposure dose (Tchounwou et al., 2012). The toxicity and carcinogenicity caused by heavy metals include several mechanistic aspects, some of which are not explicitly elucidated or understood (Tchounwou et al., 2012).

However, it is known that each metal has unique characteristics and Physico-chemical properties which confer its specific toxicological mechanisms of action. To mention a few, studies have shown that Cd-toxicity target organs include the liver, brain, lungs, kidneys, and the placenta (Sobha et al., 1970). The signs of impact, depending on the severity of the exposure, include vomiting, nausea, stomach cramps, dyspnea, and muscle weakness. Not only Cd but Cu according to Singh & Kalamdhad (2011) can lead to severe mucosal corrosion and irritation, damage to capillaries, hepatic and renal damage, and irritation of the spinal cord following excessive intake.

Again, it has also been reported that acute Pb poisoning can lead to brain, liver, reproductive system, and kidney dysfunction resulting in illness and death (Odum et al., 2016). As toxicity often presents a condition akin to and frequently associated with, Guillain-Barre syndrome, an anti-immune disorder that occurs when part of the PNS is mistakenly targeted by the body's immune system, leading to nerve inflammation that causes muscles to weaken (Duruibe et al., 2007). In addition to this, Duruibe et al. (2007) have also noted that exposure to mercury poses risk to gingivitis, stomatitis, neurological disorders, complete brain, and CNS injury, as well as congenital defects.

At the recycling site, various activities are specific to each part of the site, although some of these activities cut across the entire recycling site. Amidst, the e-waste recycling activities, children play on the soiled ground blackened from oil and fires, while women cook food for the workers. Additionally, next to the recycling site is a busy produce market with a major proportion of the vegetables sold here being grown around the e-waste site. Yet given the myriad health risks that have been associated with heavy metal exposure, contamination beyond pollution sources remained understudied, this study, therefore, investigated the movement of heavy metals from their sources of generation across space to assess the extent of contamination and the risk they posed to individuals who plied their trade around the area, food grown and sold around the vicinity, as well as residents around the Agbogbloshie e-waste area.

CHAPTER 3

3.0 METHODOLOGY

3.1 Study area

The study was conducted at the e-waste site in Agbogbloshie. This study site is previously described (Simon, 2018; Srigboh et al., 2016; Asante et al., 2012). In brief, the Agbogbloshie e-waste site is arguably one of the largest e-waste dumps in the world. Ghana has a market for second-hand electronic devices, and large proportions of the electronics imported are old, near, or at end-of-life, with little or no utility value. Once in Ghana, shipments are likely to show up here. The area is flat, heavily industrialized, and densely populated, with a scattering of recyclers working out of small shelters and in the open (Srigboh et al., 2016). The popular Agbogbloshie Market, which sells all major food products and farm produce, is located nearby. The site is bordered on the east by the Korle Lagoon and on the west by the Odaw River. Much of the site is flooded during periods of heavy rainfall (Huang, Nkrumah, Anim, & Mensah, 2014), and surface dust and sediments, as well as any chemical contaminants they may contain, are likely to be transferred into the nearby soils and the Odaw River which then empties into the ocean (Oteng-Ababio, 2012).

3.2 Description of study site

The study site with a relatively flat topography was demarcated into three workspaces depending on the activities carried out on the space, viz. sorting, dismantling, and burning. In the sorting area, an assortment of e-waste collected along the breadth and length of the capital are offloaded and separated into different components. In the second area, electronic wastes are broken down using tools such as screwdrivers and hammers. At the burning area, fire is used to burn plastics off of electronic wires and coils to retrieve metals of interest. Numerous temporary fires are used within the open areas to incinerate plastics and other combustible materials from individual batches of materials. Such small fires are frequently set at the preceding fire sites, resulting in an accumulation of ash and partially burned materials.

3.3 Type of study

The study was an analytical cross-sectional study. Samples (topsoil, subsoil, and water) were taken from the site at a single point in time for analysis to measure the concentrations of heavy metals.

3.3 Variables

3.3.1 Dependent Variables

The dependent variables were concentrations of As, Pb, Cd, and Hg in soil and water.

3.3.2 Independent Variables

The independent variable for the study was e-waste recycling activities across different workspaces.

3.3 Sample collection and preparation

A total of 76 soil samples were collected from the site along a marked transect, twenty meters away from each sampling point. Soil samples were collected from approximate centres and positions marked across cardinal directions across workspace (sorting, dismantling, and burning) using a soil augur. And thus, an approximate centre of these workspaces was marked and defined as pollution sources. From each pollution source, a distance of 20m, 40m, and 60m across all cardinal directions were marked using a handheld global positioning system (GPS) device (Gamin eTrex 10). At each location, one sample was collected at a depth of 0 to 20cm (topsoil) and from 20 to 60 cm (subsoil). The soil auger was cleaned with concentrated trioxonitrate (VI) acid (HNO_3) before and after sampling at each point to eliminate every bit of metals that could contaminate the soil samples. The soil samples were then labelled and stored in Ziploc bags.

Water samples were drawn from the Odaw river into six individual 500-millilitre plastic bottles using a bucket with a 3-litre capacity and two ropes tied to two opposing ends of the bucket. From a single water point (either upstream, midstream, or downstream), 2 water samples were collected. Bottles for the sample collection were washed thoroughly with detergent and rinsed with concentrated trioxonitrate (VI) acid (HNO_3) and water. This was done to eliminate any bit of agents that could interfere with the analysis. All the water samples were then labelled, stored and transported in ice-packed coolers to ECOLAB at the University of Ghana where heavy metal concentrations were analyzed. Figures 3.1, 3.2, and 3.3 below represent the points selected and marked across each workspace.

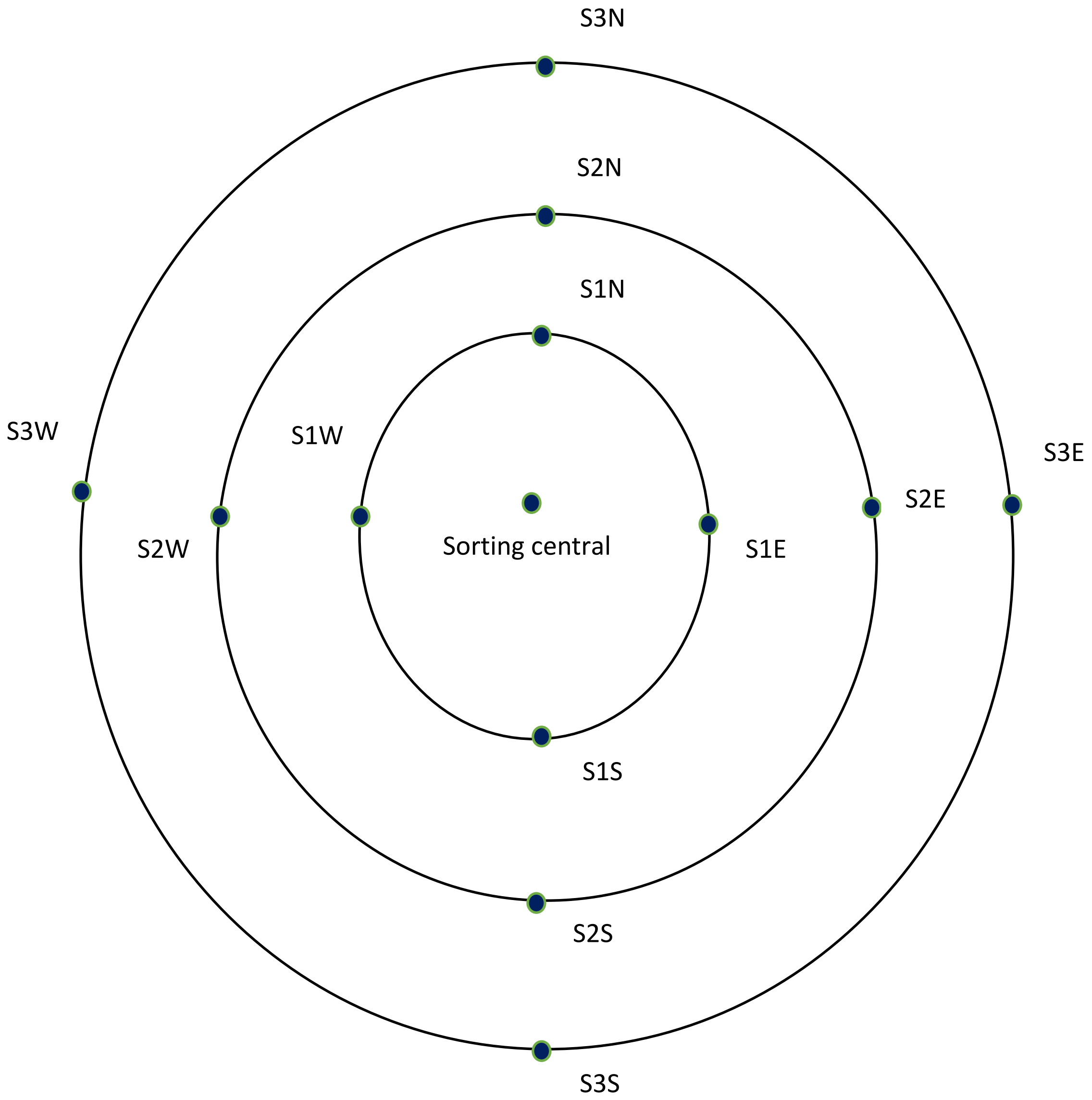

Figure 3.1: Sample collection points at/around the sorting area at equi-spatial distances in different directions. (Not drawn to scale)

Legend:
SC represents Sorting site Central point
S1N represents Sorting site North point 1
S2N represents Sorting site North point 2
S3N represents Sorting site North point 3
S1W represents Sorting site West point 1
S2W represents Sorting site West point 2
S3W represents Sorting site West point 3
S1S represents Sorting site South point 1
S2S represents Sorting site South point 2
S3S represents Sorting site South point 3
S1E represents Sorting site East point 1
S2E represents Sorting site East point 2
S3E represents Sorting site East point 3

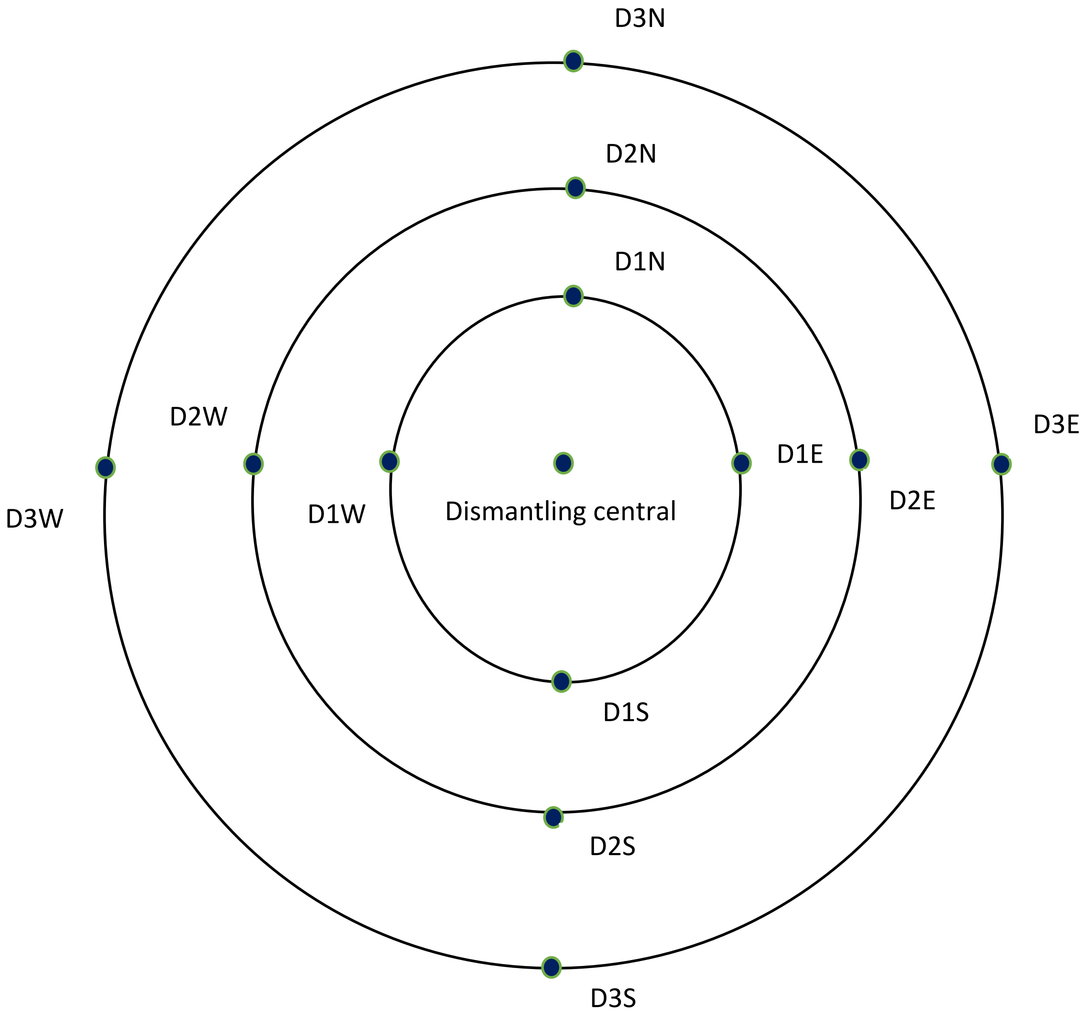

Figure 3.2: Sample collection points at/around the dismantling area at equi-spatial distances in different directions. (Not drawn to scale)

Legend:
DC represents Dismantling site Central point
D1N represents Dismantling site North point 1
D2N represents Dismantling site North point 2
D3N represents Dismantling site North point 3
D1W represents Dismantling site West point 1
D2W represents Dismantling site West point 2
D3W represents Dismantling site West point 3
D1S represents Dismantling site South point 1
D2S represents Dismantling site South point 2
D3S represents Dismantling site South point 3
D1E represents Dismantling site East point 1
D2E represents Dismantling site East point 2
D3E represents Dismantling site East point 3

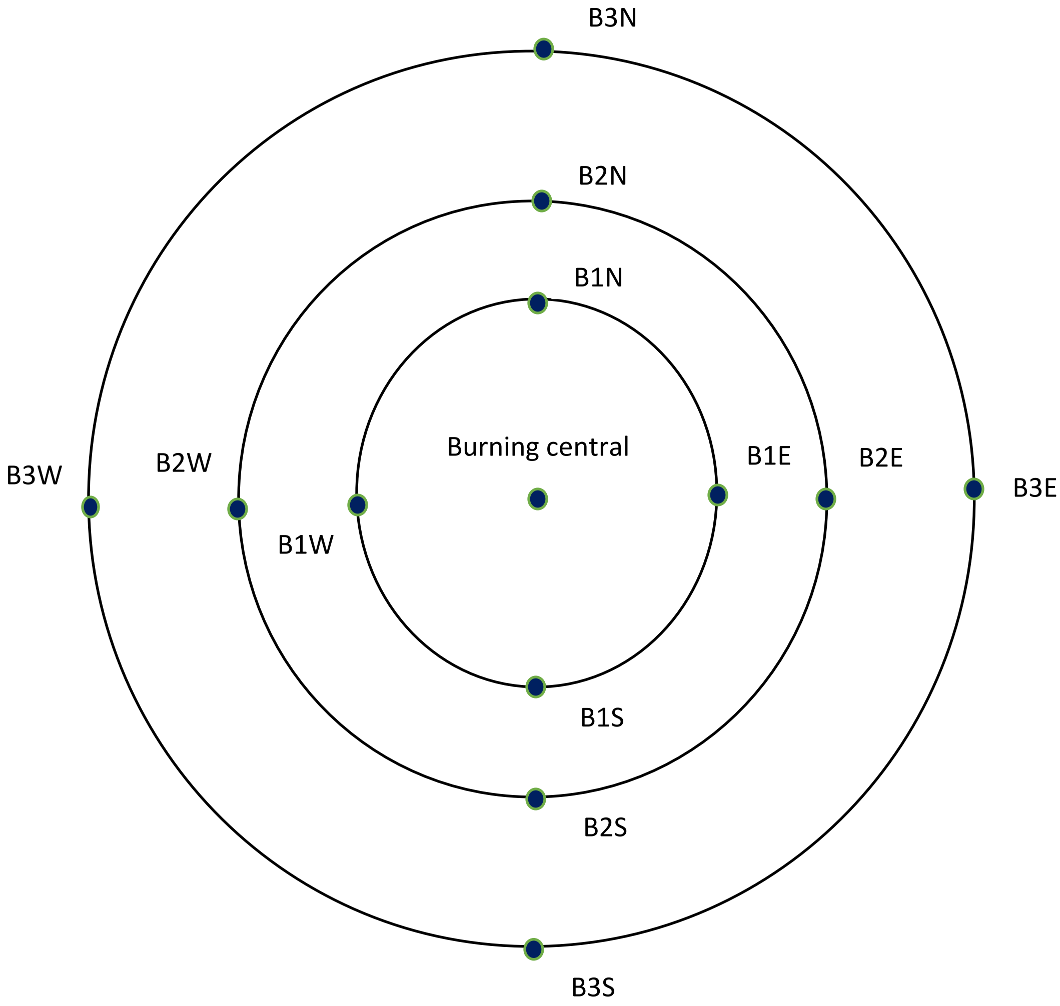

Figure 3.3: Sample collection points at/around the burning area at equi-spatial distances in different directions. (Not drawn to scale)

Legend:

BC represents Burning site Central point
B1N represents Burning site North point 1
B2N represents Burning site North point 2
B3N represents Burning site North point 3
B1W represents Burning site West point 1
B2W represents Burning site West point 2
B3W represents Burning site West point 3

B1S represents Burning site South point 1
B2S represents Burning site South point 2
B3S represents Burning site South point 3
B1E represents Burning site East point 1
B2E represents Burning site East point 2
B3E represents Burning site East point 3

3.4 Sample analysis

3.4.1 Soil sample

After air-drying, a 2mm mesh was used to sieve the soil sample. 1g of each sample of dried soil was weighed and digested at 145^{o}C with 3mL concentrated nitric acid (HNO_3) in Folin-Wu tubes in an electrically heated block for 1hr. The tubes were cleaned and purified with concentrated nitric acid (HNO_3) and water and 4ml of perchloric acid ($HCLO_4$) was added and then heated for an additional hour to a temperature of 240^{o}C. After allowing the solutions to cool, they were then filtered into a 100 ml Pyrex volumetric flask using a 100 ml Whatman No 42 filter. It was then topped up with distilled water to increase it to the 100 ml mark. Using a PinAAccle 900T Atomic Absorption Spectrophotometer with a particular wavelength for each metal, 193.7 nm for As, 228.8 nm for Cd, 217.0 nm for Pb, and 253.7 nm for Hg, the solutions were analyzed for heavy metal concentrations. For each determination, the average values of three replicates were taken. An appropriate drift blank was taken before the sample analysis.

3.4.2 Water sample

The acidified water samples were vigorously mixed and immediately aspirated using a PinAAccle 900T Atomic Absorption Spectrophotometer for the determination of Hg, As, Cd, and Pb levels. For each determination, the average values of three replicates were taken. An appropriate drift blank was taken before the sample analysis. The working wavelength for the heavy metals was 228.8 nm for Cd, 253.7 nm for Hg, 193.7 nm for As, and 217.0 nm for Pb.

3.5 Analysis of data

The data was entered using excel and later exported into STATA version15 (Stata Corps, Chicago, USA) for the appropriate analysis. Means and standard deviations were used to describe the data obtained from the lab analysis.

3.5.1 Variation of heavy metals concentration in soil across job tasks

To begin with, a histogram was plotted to ascertain the normality of the distributed data. To verify for the existence of any significant differences between the mean values obtained for the levels of heavy metals in soil across job tasks (sorting, dismantling, and burning), analysis of variance (ANOVA) at a significant level of 95% confidence interval were conducted.

3.5.2 Estimation of level of soil contamination across job tasks

For this study, the relative gradation of soil heavy metal contamination was evaluated across job tasks using pollution indices; contamination degree (CD), contamination factor (CF), as well as the pollution load index (PLI).

3.5.3 Classification of CF of soil heavy metals across job tasks

The CF was used to evaluate the accumulation of the soil heavy metals across job tasks. The CF that evaluates the contamination of the soil by a single metal was expressed as $CF_{metals} = C_{metal}/C_{SGV.}$ Here, CF_{metals} is the contamination factor, C_{metal} denotes the concentration of metal in the studied sample and C_{SGV} is the background value of individual metals (Chan et al., 2001). Four contamination categories are assigned based on contamination factor: $CF<1$= low degree of contamination, $1 \leq CF<3$ = moderate degree of contamination, $3 \leq CF<6$ = considerable degree of contamination, $CF \geq 6$= very high degree of contamination (Islam et al., 2015).

3.6.4 Classification of CD for soil heavy metals across job tasks

The CD was calculated to assess the cumulative impact of the heavy metals on the soil. This was computed using the equation: CD = $\sum_{i=1}^{n} CF$, where CF is the contamination factor. The following classification is given for contamination: CD<7= low degree of contamination, 7≤CD<14= Indicates a moderate degree of contamination, 14≤CD<28= considerable degree of contamination, CD≥28= high degree of contamination (Hassan et al., 2016).

3.6.5 Classification of PLI for soil heavy metals across job tasks

Contamination severity and its variation across the job tasks were evaluated with the use of pollution load index. The PLI was computed using: $\mathrm{PLI} = \sqrt[n]{CF_1 . CF_2 \ . \ CF_3 . \ \ldots \ . \ CF_n}$ Here, n denotes the number of metals investigated and CF's; the contamination factors of metals investigated (Angulo, 1996). The PLI indicates perfection (no pollution), presence of only baseline level of pollutants, pollution or progressive deterioration of the site and soil quality when PLI=0, PLI=1, and PLI respectively= >1 (Islam et al., 2015).

3.6.5 Comparison of heavy metals concentration in the Odaw river to WHO standards

The mean levels of heavy metals in water across the different sections (upstream, midstream, and downstream) on the Odaw river were compared to the World Health Organization recommended levels in water (WHO, 2011).

CHAPTER 4

4.0 RESULTS

The percentage recovery of spiked samples ranged from 97.9-99.6% and the certified reference materials analyzed were in agreement with certified values. The precision was found to be within ± 5% for all metals which validated the experimental procedure used for the analysis.

4.1 Variation in concentration of heavy metals in surface soil across job tasks

All metals of interest (Pb, Cd, Hg, and As) were recorded in surface soil across job tasks (burning, dismantling, sorting). The heavy metal concentrations ranged from 5.11-121.20 mg/kg for Cd, 0.27-21.40 mg/kg for As, 0.13-18.89 mg/kg for Hg, among the job tasks. For all metals studied, the mean concentration for each was highest in topsoil collected from burning area; e.g, Cd (58.77±27.43), Pb (342.26±222.56), As (4.82±2.63), and Hg (3.76±2.32). The mean concentrations of the heavy metals in topsoils collected from both dismantling and sorting areas were comparable but quite irregular in pattern from one element to the other as the mean concentration of As and Hg. The lowest concentrations of As and Hg with mean values of 2.74 mg/kg and 1.92 mg/kg respectively were recorded across the sorting surface soils, whereas the lowest mean values for Cd (41.84 mg/kg) and Pb (144.24 mg/kg) were recorded across the dismantling surface soils. Analysis of variance (ANOVA) at 95% confidence interval revealed a significant ($P < 0.05$) variation in the concentrations of Pb, Cd, As, and Hg across the job tasks, which indicated the variations in heavy metals concentration across the different job tasks and the extent of spread across the surface soils. Table 4.1 presents the summary of the mean concentrations of Cd, Pb, As, and Hg analyzed in the surface soil samples collected across the different job tasks at the Agbogbloshie e-waste site in the Greater Accra region of Ghana.

4.2 Dispersal of heavy metals across cardinal directions from a burning point source

Varying levels of all metals found at the burning point source (epicentre) were also recorded across all cardinal directions. For all the metals studied, the mean concentration for each was highest in soil collected from the epicentre; e.g., Cd (97.27 mg/kg), Pb (721.67 mg/kg), As (21.23 mg/kg), and Hg (18.85 mg/kg). The mean concentrations of the heavy metals in soils collected across cardinal directions, however, were comparable, but quite irregular in their distribution from one element to the other as some heavy metal levels increased with increasing distance while others reduced with increasing distance. For example, heavy metal levels were observed to decrease markedly across cardinal directions as the soil sampling distance from the epicenter increased (Table 4.2) except for those observed at the third sampling point (B3N, B3E, B3W, B3S) with mean values: Cd (90.97 mg/kg), Pb (153.67 mg/kg), As (3.38 mg/kg) and Hg (2.44 mg/kg) in the north direction, Cd (50.99 mg/kg), Pb (453.67 mg/kg), As (3.96 mg/kg) and Hg (2.86 mg/kg) in the south direction, Cd (121.07 mg/kg), Pb (161.73 mg/kg), As (3.22 mg/kg) and Hg (2.66 mg/kg) in the east direction and Cd (77.03 mg/kg), Pb (467.13 mg/kg), As (2.77 mg/kg) and Hg (1.88 mg/kg) in the west direction. Meanwhile, the highest concentrations of Pb were recorded in the south direction, and the highest concentrations of Cd were recorded in the east direction (Table 4.2). On average, heavy metal concentrations at the epicentre and across the cardinal directions were generally higher for Pb and lowest for Hg. The general trend in the dispersion pattern of heavy metals in soil across cardinal directions from a burning point source at the Agbogbloshie e-waste site was Pb > Cd > As > Hg. Table 4.2 summarizes the mean concentrations of Pb, Cd, As, and Hg at the burning point source and across cardinal directions of the Agbogbloshie e-waste site.

4.3 Dispersal of heavy metals from a dismantling point source across cardinal directions

Different measures of all metals found at the dismantling point source (epicentre) were also recorded across all cardinal directions. For all the metals analyzed, the mean concentration for each was lowest in soil collected from the epicentre: Pb (22.60 mg/kg), Hg (0.57 mg/kg), Cd (5.14 mg/kg), and As (0.76 mg/kg). Although the heavy metal concentration across cardinal directions was quite irregular in pattern from one element to the other, the levels of the heavy metals observed were relatively higher across cardinal directions as compared to the levels recorded at the epicentre; e.g., Pb (31.57 mg/kg), Cd (31.07 mg/kg), As (2.22 mg/kg), and Hg (1.86 mg/kg) in the north direction and Pb (50.33 mg/kg), Cd (150.73 mg/kg), As (4.42 mg/kg) and Hg (3.98) in the south direction. The heavy metal with the highest concentration at the epicentre was Pb (22.60 mg/kg) while Hg recorded the lowest concentration with the mean value of 0.57 mg/kg. Similarly, across the cardinal directions, Pb recorded the highest levels with Hg recording the least levels (Table 4.3). As the sampling distance increased, there was a marked increase in Pb and Cd across the east direction. Pb increased to 99.17 mg/kg from 51.10 mg/kg and Cd increased to 229.277 mg/kg from 136.93 mg/kg. On the contrary, except for the third sampling point (D3E), Hg and As increased with distance, recording a mean value of 3.22 mg/kg for As and 2.26 mg/kg for Hg in the east direction, and 2.77 mg/kg for As and 1.88 mg/kg for Hg in the west direction. The concentrations of As and Hg in the soil increased markedly as the sampling distance from the epicentre increased in the north direction (Table 4.3). The general trend in the dispersion pattern of heavy metals in soil across cardinal directions from a dismantling point source at the Agbogbloshie e-waste site was Pb > Cd > As > Hg. A summary of the mean concentrations of Pb, Cd, As and Hg at the dismantling point source and across cardinal directions is presented in Table 4.3.

4.4 Dispersal of heavy metals across cardinal directions from a sorting point source

Varying levels of all metals investigated were recorded at the sorting point source (epicentre) and across the cardinal directions. For all the metals studied, the mean concentration for each was lowest in soil collected from the epicenter; Pb (15.37 mg/kg), Hg (0.98 mg/kg), Cd (9.86 mg/kg) and As (0.28 mg/kg). The mean concentrations of the heavy metals in soils collected across cardinal directions were comparatively higher but quite irregular in pattern from element to the other as the mean concentration of Pb (Table 4.4); e.g., while Pb levels decreased as the distance from the epicentre increased in the north and west directions at all sample collection points, Pb levels recorded at S3E and S3S were much higher in the east and south directions although heavy metal levels were observed to decrease as the distance from the epicentre increased (Table 4.4). Except for the concentrations recorded at S3W and S3S, the level of Hg decreased markedly as the distance from the epicentre increased across all cardinal directions. Similarly, except for the concentration recorded at S3S, the mean concentration of Hg recorded across all cardinal directions reduced significantly as the distance from the epicentre increased. The general trend in the dispersion pattern of heavy metals in soil across cardinal directions from the sorting point source at the Agbogbloshie e-waste site was Pb > Cd > As > Hg. Table 4.4 presents a summary of the mean concentrations of Pb, Cd, As, and Hg at the sorting point source and across cardinal directions.

4.5 Variation of heavy metals concentration in subsoil across job task

All metals of interest were recorded at varying concentrations at different depths of the soil across job tasks (dismantling, sorting, and burning). For all the metals studied, the mean concentration for each was highest at Depth 1 (0-20cm) collected from the burning area; e.g., Cd (58.76 mg/kg), Pb (342.26 mg/kg), As (4.81 mg/kg), and Hg (3.76 mg/kg). The mean concentrations of the heavy metals at Depth 1 collected from both dismantling and sorting areas, however, were comparable but quite irregular in pattern (Table 4.5). In contrast, although the mean concentrations of the heavy metals at Depth 2 across all job tasks (burning, dismantling, and sorting) were comparable, they were quite irregular in pattern. However, comparatively, the mean concentrations of Pb, Cd, As and Hg recorded at a 0-20cm depth were much higher than concentrations found in soil collected at 20-60cm depth across the burning workspace (Table 4.5). On the contrary, the mean concentrations of Hg (2.53 mg/kg), Cd (56.22 mg/kg), and As (3.35 mg/kg) recorded at a depth of 20-60cm across the sorting workspace were relatively higher than those reported at a depth of 0-20cm, except for Pb, which was relatively higher at a depth of 0-20cm than at a depth of 20-60cm. Pb recorded higher concentrations of all metals investigated at both depths across job tasks with a mean value of 342.26 mg/kg and 210.47 mg/kg for burning, 252.39 mg/kg and 240.06 mg/kg for sorting, and 172.32 mg/kg and 237.23 mg/kg for dismantling respectively. The mean values of 67.09 mg/kg and 237.23 mg/kg recorded for Pb and Cd across the dismantling workspace were relatively higher at a depth of 20-60cm compared to the depth of 0-20cm (Table 4.5). Across burning, sorting, and dismantling workspaces, Hg and As concentrations were relatively higher at a depth of 0-20 cm, except for the sorting workspace where the concentrations of As and Hg were relatively lower (Table 4.5). In decreasing order of abundance, the heavy metal concentrations across the burning, dismantling, and sorting job tasks were in the order: Pb > Cd > As > Hg at both 0-20cm and 20-60cm depths. The concentrations of the metals investigated were significantly lower ($P < 0.05$) in the subsoil than the topsoil. Variations of Pb, Cd, As and Hg across job tasks at different soil depths are presented in Table 4.5.

4.6 Variation of heavy metals in water from different sampling points on the Odaw river

The water from the Odaw river exhibited distinct variations in the levels of heavy metals. Cd, Pb, As, and Hg concentrations ranged from 0.316 mg/kg - 0.633 mg/kg, 0.087 mg/kg - 0.231 mg/kg, 0.002 mg/kg - 0.043 mg/kg, and 0.002 mg/kg - 0.015 mg/kg in the Odaw river respectively. For all water samples analyzed, the mean concentrations of the heavy metals upstream, midstream, and downstream were comparable but quite irregular in pattern. Cd concentrations were comparatively higher than all metals investigated, recording the mean values of 0.382 mg/kg, 0.443 mg/kg, and 0.576 mg/kg in the upstream (area before entering the e-waste site), midstream (area where actual burning takes place) and downstream (the area away from the actual burning site) respectively. Hg reported the lowest concentrations of all the heavy metals investigated, with mean values of 0.002 mg/kg, 0.003 mg/kg, and 0.003 mg/kg in the upstream, midstream, and downstream respectively, followed closely by As which recorded 0.003 mg/kg in the upstream, 0.005 mg/kg in the midstream and 0.005 mg/kg in the downstream respectively. Compared to 0.382 mg/kg and 0.443 mg/kg recorded in the upstream and midstream respectively, Cd concentration recorded in the downstream was comparatively higher while As and Hg recorded the same concentrations as those obtained in the midstream. Almost all mean concentrations recorded in the upstream were the lowest, except for Cd concentrations. Pb and Cd were the dominant heavy metals recorded in the Odaw river. Elevated levels of these metals were recorded in the midstream and downstream. In considering the mean concentration, the distribution of heavy metals in the water from the Odaw river was in the increasing order: Cd > Pb > As > Hg. A summary of the mean concentrations of heavy metals in water from different points on the Odaw river is presented in Table 4.6.

4.7 Classification of contamination factor (CF) of heavy metals in surface soil across job tasks

The values of the CF for Cd across all job tasks: burning, dismantling, and sorting were greater than six (CF ≥ 6) and this suggested that there was a high degree of Cd contamination in the soil across workspaces. On the contrary, a low degree of As contamination was observed across job tasks as the values of CF obtained for burning, dismantling, and sorting were all less than one (CF < 1). The CF of Pb obtained across burning, sorting, and dismantling workspaces fell between three and six (3 ≤ CF < 6) implying that there was a considerable degree of Pb contamination in the soil. Similarly, CF values for Hg fell between one and three (1 ≤ CF < 3) signifying that there was a moderate degree of Hg contamination in soil across burning, sorting, and dismantling workspaces. The CF of Pb, Cd, As and Hg in soil across burning, dismantling, and sorting areas are presented in Table 4.7.

4.8 Classification of contamination degree (CD) for surface soil heavy metals across job tasks

According to the CD values: 26.81, 24.55, and 23.62 (Table 4.7), all samples collected across the job tasks (burning, dismantling, and sorting) were at high contamination since the CD values recorded across the job tasks were all greater than twenty-eight (CD > 28).

4.9 Classification of pollution load index (PLI) in surface soil across job tasks

After computing the PLI, the values 2.36, 2.25, and 1.97 were obtained for burning, sorting, and dismantling job tasks respectively. The results of this study showed that PLI values presented in Table 4.7 were generally high (PLI = >1) across burning, sorting, and dismantling workspaces indicating a progressive deterioration of the soil across the site. Based on the results presented in

Table 4.7, the contamination of soil across job tasks by Pb, Cd, As and Hg was in the order: burning > dismantling > sorting.

4.10 Classification of contamination factor (CF) of heavy metals in subsoil across job tasks

The CF values for Cd were greater than six across all job tasks: burning, dismantling and sorting ($CF \geq 6$) and this indicated that there was a high degree of Cd contamination in the soil across job tasks. However, there was a low degree of As contamination in soil across burning, dismantling, and sorting job tasks ($CF < 1$). Meanwhile, there was a considerable degree of Pb contamination ($3 \leq CF < 6$) in the subsoil across burning, sorting, and dismantling workspaces. Likewise, CF values for Hg fell between one and three ($1 \leq CF < 3$) suggesting that there was a moderate degree of Hg contamination across burning, sorting, and dismantling job tasks. Table 4.8 presents the CF of Pb, Cd, As and Hg in subsoil across the burning, dismantling, and sorting job tasks.

4.11 Classification of contamination degree (CD) for subsoil heavy metals across job tasks

Generally, according to the CD values: 24.59, 28.46, 24.98 (Table 4.8), the subsoil across job tasks were highly contaminated, as the computed CD values for subsoil across burning, sorting, and dismantling workspaces were all greater than twenty-eight ($CD > 28$).

4.12 Classification of pollution load index (PLI) in subsoil across job tasks

After computing the PLI, the values 2.64, 2.12, and 2.10 were obtained for burning, sorting, and dismantling job tasks respectively. The results of this study (as shown in Table 4.8) were generally high ($PLI = >1$) across burning, sorting, and dismantling workspaces indicating a progressive deterioration of the subsoil across the site. Based on the results presented in Table 4.8, the contamination of subsoil across job tasks by Pb, Cd, As and Hg was in the order: burning > dismantling > sorting.

Table 4.1: Variation of heavy metals concentration in surface soil across burning, sorting, and dismantling job tasks

Metal \ Environmental Medium	Burning			Dismantling			Sorting		
	Min.	Mean ± S.D	Max.	Min.	Mean ± S.D	Max.	Min.	Mean ± S.D	Max.
Cd	20.10	58.77±27.43	121.20	5.11	41.84±24.09	99.70	9.79	51.42±17.36	88.70
Pb	12.10	342.26±222.56	713.30	6.60	144.24±94.61	571.90	15.30	175.04±115.88	444.20
As	2.33	4.82±2.63	21.40	0.74	3.33±1.54	7.76	0.27	2.74±0.88	4.43
Hg	1.67	3.76±2.32	18.89	0.56	2.60±1.30	5.44	0.13	1.92±0.62	3.21

Table 4.1 shows the variation of heavy metal concentration in surface soil across job task and for all the metals studied, the mean concentration for each was highest in topsoil collected from burning area; e.g., Cd (58.77±27.43), Pb (342.26±222.56), As (4.82±2.63) and Hg (3.76±2.32). The mean concentrations of the heavy metals in topsoils collected from both dismantling and sorting areas were comparable but quite irregular in pattern from one element to the other as the mean concentration of Pb.

Table 4.2: Dispersal (or movement/migration) of heavy metals from a burning point source (BC=Burning Centre) across cardinal directions

Metal \ Direction	Central	North			South			East			West		
	BC	B1N	B2N	B3N	B1S	B2S	B3S	B1E	B2E	B3E	B1W	B2W	B3W
Cd	97.27	44.97	20.10	90.97	44.17	50.97	50.99	85.80	21.73	121.07	37.13	21.73	77.03
Pb	712.67	578.63	81.63	153.67	437.10	337.33	453.67	695.97	12.20	161.73	246.40	178.23	467.13
As	21.23	4.11	2.76	3.38	5.48	4.10	3.96	3.23	2.77	3.22	2.98	2.73	2.77
Hg	18.85	3.42	1.87	2.44	3.22	2.85	2.86	2.98	2.10	2.66	1.75	1.99	1.88

Table 4.2 shows the dispersal of heavy metals from a source of generation (BC=Burning Centre) across cardinal directions and for all the metals studied, the mean concentration for each element was highest at burning centre; e.g. Cd (97.27), Pb (712.67), As (21.23), and Hg (18.85). The mean concentrations of the dispersed heavy metals in soil collected across cardinal directions were comparable but uneven in their dispersal pattern from one element to the other as levels fluctuated along with cardinal directions.

Table 4.3: Dispersal (or movement/migration) of heavy metals from a dismantling point source (DC=Dismantling Centre) across cardinal directions

Metal \ Direction	Central	North			South			East			West		
	DC	D1N	D2N	D3N	D1S	D2S	D3S	D1E	D2E	D3E	D1W	D2W	D3W
Cd	5.14	31.57	33.03	67.00	50.33	39.73	51.33	51.00	89.20	99.17	77.53	30.87	28.07
Pb	22.60	31.07	571.43	163.43	150.73	209.77	136.93	136.93	229.27	151.00	290.93	6.63	99.73
As	0.76	2.22	4.86	4.36	4.42	7.75	3.25	4.39	3.40	4.33	4.32	2.65	4.32
Hg	0.57	1.86	3.44	4.46	3.98	5.43	2.29	3.95	2.65	3.55	3.42	1.88	2.41

Table 4.3 shows the dispersal of heavy metals from a source of generation (DC=Dismantling Centre) across cardinal directions and for all the metals studied, the mean concentration for each element was lowest at the dismantling centre; e.g. Cd (5.14), Pb (22.60), As (0.76), and Hg (0.57). The mean concentrations of the dispersed heavy metals in soil collected across cardinal directions were comparable but uneven in their dispersal pattern from one element to the other as levels fluctuated along with cardinal directions.

Table 4.4: Dispersal (or movement/migration) of heavy metals from a sorting point source (SC=Sorting Centre) across cardinal directions

Metal \ Direction	Central	North		South			East			West		
	SC	S1N	S2N	S1S	S2S	S3S	S1E	S2E	S3E	S1W	S2W	S3W
Cd	9.86	48.43	29.15	55.87	35.47	86.00	64.93	87.80	56.93	51.20	61.17	121.93
Pb	15.37	123.47	69.42	444.10	101.07	143.57	198.98	104.60	309.7	442.70	118.13	78.93
As	0.28	4.36	2.32	9.33	3.33	4.15	3.25	2.92	2.34	3.25	1.97	1.98
Hg	0.98	1.80	1.37	3.12	2.22	3.15	2.89	1.77	1.56	1.92	1.13	1.12

Table 4.3 shows the dispersal of heavy metals from a source of generation (DC=Sorting Centre) across cardinal directions and for all the metals studied, the mean concentration for each element was lowest at the sorting centre; e.g. Cd (9.86), Pb (15.37), As (0.28), and Hg (0.98). The mean concentrations of the dispersed heavy metals in soil collected across cardinal directions were comparable but uneven in their dispersal pattern from one element to the other as levels fluctuated along with cardinal directions.

Table 4.5: Variation of heavy metals concentration in subsoil across burning, sorting, and dismantling job tasks

Metal \ Environmental Medium	Burning		Dismantling		Sorting	
	Depth 1	Depth 2	Depth 1	Depth 2	Depth 1	Depth 2
Cd	58.76	56.16	50.31	67.09	49.35	56.22
Pb	342.26	210.47	172.32	237.23	252.39	240.06
As	4.81	3.16	3.92	3.23	3.07	3.35
Hg	3.76	2.20	3.07	2.48	2.20	2.53

Table 4.5 shows the variation of heavy metal concentration at different depths across job task and for all the metals studied, the mean concentration for each was highest in soils collected at Depth 1 from burning area; e.g., Cd (58.76), Pb (342.26), As (4.81) and Hg

(3.76). The mean concentrations of the heavy metals in soils collected at Depth 1 from both dismantling and sorting areas and Depth 2 across job tasks were comparable but irregular in the pattern of distribution from one element to the other.

Table 4.6: Variation of heavy metals in water from different sampling points on Odaw river

Metal \ Environmental Medium	Upstream			Midstream			Downstream		
	Min.	Mean ± S.D	Max.	Min.	Mean ± S.D	Max.	Min.	Mean ± S.D	Max.
Cd	0.316	0.382 ± 0.063	0.447	0.392	0.443 ± 0.050	0.493	0.519	0.576 ± 0.054	0.633
Pb	0.158	0.192 ± 0.031	0.231	0.087	0.112 ± 0.023	0.141	0.132	0.136 ± 0.003	0.143
As	0.002	0.003 ± 0.001	0.043	0.003	0.005 ± 0.001	0.007	0.003	0.005 ± 0.001	0.005
Hg	0.015	0.002 ± 0.001	0.003	0.002	0.003 ± 0.001	0.004	0.002	0.003 ± 0.001	0.003

Table 4.6 shows the variation of heavy metal concentration in water from different sampling points on Odaw river, the mean concentration for each was highest in water collected from downstream; e.g., Cd (0.576±0.054), Pb (0.136±0.003), As (0.005±0.001), and Hg (0.003±0.001). The mean concentrations of the heavy metals in water collected from both upstream and midstream sections of the river were comparable but quite irregular in pattern from one element to the other as the mean concentration of Cd.

Table 4.7: Classification of pollution indicators (CF, CD, and PLI) for heavy metals in surface soil across job tasks

Pollution indices	Heavy metals	Burning	Dismantling	Sorting
CF	Cd	19.59	17.59	18.86
	Pb	5.52	4.92	3.16
	As	0.19	0.16	0.18
	Hg	1.51	1.88	1.42
CD		26.81	24.55	23.62
PLI		2.36	2.25	1.97

Table 4.7 shows the gradation of the pollution indices computed for surface soil heavy metals across job tasks with CFs of elements; As, Hg, Pb and Cd suggesting increasing surface soil contamination from low to very high across burning, sorting and dismantling job tasks and the CD and PLI values indicating a progressive deterioration of the surface soil across burning, sorting and dismantling job tasks.

Table 4.8: Classification of pollution indicators (CF, CD, and PLI) for heavy metals in subsoils across job tasks

Pollution indices	Heavy metals	Burning	Dismantling	Sorting
CF	Cd	18.72	22.36	18.74
	Pb	4.21	4.74	4.80
	As	0.56	0.16	0.17
	Hg	1.10	1.20	1.27
CD		24.59	28.46	24.98
PLI		2.64	2.12	2.10

Table 4.8 shows the gradation of the pollution indices computed for subsoil heavy metals across job tasks with CFs of elements; As, Hg, Pb and Cd suggesting increasing subsoil contamination from low to very high across burning, sorting and dismantling job tasks and the CD and PLI values

indicating a progressive deterioration of the subsoil across burning, sorting and dismantling job tasks.

CHAPTER 5

5.0 DISCUSSION

5.1 Introduction

While there is a growing body of evidence suggesting movement of heavy metals from pollution sources to adjacent soil and available surface water as well as groundwater across e-waste sites, the evidence base is relatively scanty, and more studies are needed to establish a strong foundation for informed decisions on the approach to contamination reduction, reducing human vulnerability, and protecting the public from heavy metals exposure risk. Having the notoriety as one of the most contaminated e-waste sites in the world with a large body of literature on soil heavy metal research around this recycling site, these previous studies at Agbogbloshie are limited to just contamination in surface soil at the working areas of dismantling, sorting and burning (Atiemo et al., 2012; Brigden et al., 2008; Caravanos et al., 2011; Otsuka et al., 2012; Itai et al., 2014). This research, however, investigated the migration and dispersion of heavy metal contaminants at Agbogbloshie.

5.2 Heavy metal contamination of soil

It is interesting to note that all metals of interest were detected in all 76 samples collected from the study site. This is consistent with previous studies wherein several heavy metals were detected at major waste dumpsites in China, India, and Nigeria (Awokunmi, Asaolu, & Ipinmoroti, 2010; Kanmani & Gandhimathi, 2013; Ocheje, 2013; Olafisoye, Adefioye, & Osibote, 2013; Tanee & Eshalomi-Mario, 2015; Wong, Duzgoren-Aydin, Aydin, & Wong, 2007). In general, except for As levels, all other metals of interest (Pb, Cd, and Hg) reported in this study were far above the WHO acceptable limits across job tasks. For example, the mean values of Cd, Pb, and Hg reported in this study for topsoil samples across the burning workspace were 25.1, 6.8, and 1.8 fold higher respectively, while those recorded in surface soil across the dismantling workspace were 13.9, 2.9, and 1.3 higher. Meanwhile, the mean values recorded across the sorting area were 17.14, 3.5, and 3.9 times higher than the WHO acceptable limits for Cd, Pb, and Hg respectively.

Similarly, except for the concentrations of As recorded across job tasks, the levels of all heavy metals of interest recorded in this study for deep soils were also far above the WHO acceptable limit of 50 mg/kg for Pb, 3.0 mg/kg for Cd and 2.0 mg/kg for Hg. And thus while Cd, Pb, and Hg recorded in deep soils across the burning workspace were 18.7, 4.2, and 1.1 times higher, the subsoils from the dismantling workspace were 22.4, 4.7, and 1.2 times higher. The deep soils collected across the sorting workspace were also 18.7, 4.8, and 1.3 fold higher than the WHO acceptable soil limits for Cd, Pb, and Hg respectively. However, despite being far above the WHO acceptable soil limits, the topsoil Pb, Cd, and Hg values recorded across job tasks were elevated compared to the Cd, Pb, and Hg values recorded in deeper soils. And this is reflected in the relatively high level of pollution in the topsoil as compared to the deep soils across job tasks based on the PLI and CD indices. These are in agreement with the findings of Ipeaiyeda & Dawodu (2008) and Olafisoye, Adefioye, & Osibote, (2013) who reported a relatively high level of metals in the topsoil compared to the subsoil at an e-waste dumpsite.

The elevated heavy metal concentrations, as well as the level of pollution across the topsoil, can be attributed to the unceasing operations of e-waste workers (Atiemo et al., 2012; Bridgen et al., 2008; Otsuka et al., 2012) rather than natural enrichment through geological weathering. This assertion is supported by Olafisoye, Adefioye, & Osibote (2013) who also attributed this phenomenon to considerably fewer anthropogenic effects of supply on the subsoil than on the topsoil. However, the retention of heavy metals at the lower depth is indicative of the possible effects of leaching-related translocation. While some concentrations of heavy metals levels dropped as the distance from the pollution source increased, most concentrations of heavy metals also increased as the distance from the pollution source increased across cardinal directions, and thus heavy metal levels fluctuated with increasing distance. Notably, soil with high Pb and As were concentrated in the south and east while Hg and Cd were concentrated in the east and south of the recycling site. These findings of the current study do not support previous research by Awokunmi, Asaolu, & Ipinmoroti (2010), Chinwe, Obinna, Akeem, & Alo (2010), Fakayode & Olu-Owolabi, (2003), and Ipeaiyeda & Dawodu (2008) who noted a gradual decrease in the concentration of all heavy metals as the sampling distance increased across all cardinal directions.

Contrarily to expectation, a possible explanation for these results can be attributed to the product of runoffs and wind-blown dust. The dense cloud of smoke from burning to recover metals of value hovers over the site. As such some of the particles containing heavy metal deposits can fall at any distance across cardinal directions, contributing to metal pollution in these soils. Masindi & Muedi (2018) pointed out that that runoff results in the release of contaminants into various compartments of the environment. Added to this, it seems possible that the differences in these concentrations also reflect the activities undertaken in the area. And thus, based on the cumulative pollution indices (CD and PLI), a comparison between job tasks revealed that the burning workspace was the most contaminated (recording the highest values) with the other workspaces (dismantling and sorting) having approximately equal contamination. Certainly, the high concentration of heavy metals in the burning area and across cardinal directions is not surprising considering the major activities involved in informal e-waste recycling. These are areas of intense scrap activities within the e-waste site where non-scientific techniques are used for dismantling and burning. Both of these activities release high amounts of hazardous substances into the environment, resulting in an abnormally high degree of contamination.

However, it interesting to note that soil across the sorting workspace showed an exceptionally high level of contamination (high PLI and CD values), although a low level of contamination was anticipated due to the nature of the activities carried out there. From the burning and dismantling area, there is a thoroughfare to the Agbogbloshie main road near the sorting workspace which is used by a vast number of people leaving the scrap yard. This practice is likely to have caused the transportation of contaminants from the burning and dismantling workspaces, a plausible explanation for the high contamination of heavy metals across the sorting workspace. Atiemo et al. (2010) suggest that contaminants in the soil in this area may come from non-exhaust or exhaust sources as a result of the proximity of the sorting workspace to the road and other business entities. It is, therefore, possible that the combination of vehicular emission and activities of the scrap dealers is responsible for the high degree of contamination across the sorting workspace.

As far as the heavy metals of interest are concerned, the most obvious finding to emerge from the study was Pb as the highest metal concentration in the soil. This finding is in line with that of Olafisoye, Adefioye, & Osibote (2013), who also reported a high concentration of Pb in soil samples at various distances and depths. There are several potential reasons for this outcome. The consequence of the type of waste disposed of at the site is notable among these. The major waste materials disposed of at the site include cathode ray tubes, faulty computers, printed circuit boards, and lead-acid batteries. Awokunmi, Asaolu, & Ipinmoroti (2010) reported that a standard 15-inch cathode ray tube can contain 1.5 pounds of Pb. And thus the burning of lead-containing products perhaps could account for the high CF values for Pb recorded across the job tasks at different depths, suggesting that the soils are highly contaminated with Pb. As noted by Ogunseitan et al. (2009), short-term exposure to high lead levels can lead to vomiting, diarrhoea, seizures, coma, or even death. Awokunmi, Asaolu, & Ipinmoroti (2010) argued that Pb is particularly dangerous for young children because it affects their nervous systems readily hence impinging on learning abilities and cognitive. Similarly, in adults exposure to Pb leads to nausea, memory loss, and anorexia. Crops grown on Pb-contaminated soils absorb metals in large amounts to cause health complications for both animals and humans eating such metal-rich plants. Consequently, the accumulation of Pb in the soil can limit the functionality of the soil, causing plant toxicity, and contaminating the food chain.

Contrary to other researchers who reported relatively lower levels of Cd at dumpsites (Esakku et al., 2003; Kanmani & Gandhimathi, 2013). This result ties well with previous studies wherein elevated levels of Cd were recorded at dumpsites in Nigeria, India, and China (Campbell, 2006; Khan et al., 2008; Pradesh et al., 2013; Nduka et al., 2008; Opaluwa et al., 2012). This finding contradicts the claims made by Awokunmi et al. (2010) who argued that few products containing Cd are burned or discarded at e-waste dumpsites due to the reuse of chip resistors, infrared detectors, and semiconductors on the market, a potential explanation for recording a relatively low Cd level in the soil. Despite this, the CF value for Cd at different depths across job tasks indicates that there is a very high degree of Cd contamination in the soil. According to Shanker et al. (2005), cadmium and its compounds are used in electrical and electronic devices for a variety of applications (such as resistors and infrared detectors). And thus, the wide array of e-waste discarded or burned at Agbogbloshie may be contributing to the relatively high Cd levels in the soil. Exposure to high Cd levels can lead to severe joint pain, bone disorders, kidney and lung disorders, and anaemia (Nduka et al., 2008; Manahan, 2002).

5.3 Heavy metal contamination of water

In this study, the water Cd and Pb levels were elevated compared to the WHO (2011) guideline values for drinking water. These are in agreement with previous findings (Olafisoye et al., 2013;

Lu et al., 2019; Wu et al., 2015) wherein a relatively high level of heavy metals was recorded in surface water in the vicinity of an e-waste recycling site in Nigeria and China. It is worth emphasizing that the concentration of Pb and Cd in the Odaw river were well above permissible limits. And thus based on the mean values recorded at the upstream, midstream, and downstream, Cd was 127.3, 147.6, and 13.6 folds higher while Pb levels were 19.2, 11.2, and 13.6 folds higher than the WHO (2011) permissible limits. This is of particular concern owing to the river's strategic location and its use by humans and domestic animals in different ways.

Comparatively, high levels of Cd were found in midstream and downstream compared to upstream. These elevated concentrations observed can be attributed to anthropogenic sources such as e-waste recycling operations at the Odaw river catchment. The proximity of the midstream to the e-waste burning workspace (pollution source) could account for the elevated metal levels in this section of the river. And thus the levels implicate the magnitude of heavy metals input from erosion, atmospheric deposition, and leachates from the e-waste recycling site. It is noteworthy that all metals detected in the water are recognized to be used in electrical and electronic devices. In contrast to the lower levels of Cd recorded, the highest level of Pb recorded was in the upstream. The observed increase in Pb could be attributed to effluents from factories located along the river. According to Lough et al. (2005) and Nkwocha et al. (2017), vehicular movements release a significant amount of Pb. Given that the upstream of the river is closer to the major Agbogbloshie road, it seems possible that vehicle emissions could also be a contributor to the high Pb content in this section of the river.

Meanwhile, high concentrations of all metals investigated were found downstream as compared to the midstream and upstream. These results may be explained by the fact that heavy metals passed from the midstream end up in this section. This view is supported by Chama et al. (2014) who asserted that the upstream portion of the Odaw river that drains most industrialized and urban areas in the catchment ends up downstream. It is worth emphasizing that the potential threat heavy metals pose to the marine environment and humans depends on their concentration and persistence (Chama et al., 2014). The levels of contamination recorded in this study indicate heavy metals in the Odaw river should be considered a serious threat. Compared to a study by Fatoki et al. (2002) in which a Pb concentration of 0.1 mg/l resulted in the development of neurological problems in fetuses and infants, the results obtained in this research need immediate attention as the water is used to irrigate vegetables intended for human consumption.

Moreover, the impact of lead (Pb) on the receiving links (Korle lagoon) cannot be underestimated. This is due to the threat posed to life, especially to aquatic organisms that serve as a food source to humans. Cd is highly toxic and the use of water containing elevated levels could have adverse health effects such as kidney disease and cancer on users (Fatoki et al., 2002).

CHAPTER 6

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The soils from Agbogbloshie e-waste recycling site recorded significant levels of heavy metals. The findings herein showed that all four heavy metals (Pb, Cd, As, and Hg) found in surface soil were present in subsoil samples at pollution sources and across cardinal directions. Generally, the burning workspace had higher concentration values of all heavy metals in both surface and subsoil than the other sites. Pollution assessment revealed high contents of heavy metals in soil samples collected across job tasks. Surface soils and subsoils collected across job tasks exhibited high contamination of Cd, while they showed a considerable degree, low degree as well as a moderate degree of contamination for Pb, As, and Hg respectively. The results from the contamination factor analysis showed that the presence of heavy metals was extremely high in surface and subsoils from the burning workspace compared to other workspaces. The pollution load index and contamination degree indices showed that the most contaminated workspace was burning. The informal recycling of e-waste also has the potential to pollute the environment and nearby communities beyond the working areas of sorting, dismantling, and burning. The contamination of the environment with heavy metals poses a hazard to human health.

Similarly, all heavy metals analyzed were found in water collected from three different sections of the Odaw river, with concentrations well above WHO recommended levels in water. Except for Pb, elevated levels of Cd, As, and Hg were found in the downstream and midstream sections of the river. The results have also confirmed that the e-waste recycling activities along the banks of the Odaw river add to its contamination, suggesting man-induced contamination. As such the aquatic lives in this river are threatened since these heavy metals are considered toxic and can cause ill-health to fishes and other aquatic lives. Additionally, the health of the populations that depend on this water body for domestic and other uses are at risk.

6.2 Recommendations

- To avoid the impact of waste-related issues, education, and regulations on e-waste management should be stepped up.
- Studies need to be repeated with a wider field base instead of a few spots and to investigate the long-term impacts of heavy metals on the soil.
- An analyzer with a higher detection limit, such as ICPM-5, should be used in further analysis.
- Detailed laboratory analysis and monitoring of toxic heavy metals must be conducted periodically in environmental media (soil and water) at and around the Agbogbloshie e-waste site to assess if the levels are within reasonable limits.

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