Mercury and Other Heavy Metals Impact Assessment

Project Report

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Authors:
Blessing Gbadago; Alfonso Rodriguez; Stephan Bose-O'Reilly, Ph.D.
Esmond Wisdom Quansah, DD; Alberta Dzifa Dayie, Ph.D.; Caroline Baylor; Gabriel Sanchez Ibarra &
Ghana Environmental Protection Authority

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EXECUTIVE SUMMARY

This report provides a comprehensive assessment of mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As) pollution arising from artisanal and small-scale gold mining (ASGM) activities across 11 sites in six Ghanaian regions. The findings clarify the impact of these contaminants on various environmental media, including soil, water, air, food crops, and fish, to inform policy decisions and prioritize interventions for enhancing public health and environmental sustainability.

The ASGM sector in Ghana contributes significantly to the economy, sustaining rural development through employment. Nevertheless, the sector poses substantial environmental and public health risks due to the extensive use of mercury for gold extraction and the release of additional heavy metals from topsoil removal during the mining processes.

The Heavy Metals Impact Assessment aims to quantify contamination from mercury, lead, cadmium, and arsenic at key ASGM sites in Ghana's Ashanti, Western, Western North, Central, Eastern, and Savannah regions. Specifically, the study aims to (1) quantify heavy metal concentrations in environmental media (soil, water, food crops, fish, air), (2) identify hotspots of contamination, and (3) investigate mercury impacts within the local food system.

Methodologically, the assessment integrates stakeholder engagement, household surveys, and a rapid field screening of soil and air using portable X-Ray Fluorescence (XRF) and Jerome analyzers, complemented by laboratory-based sampling and analysis of soil, water, crops, and fish. Consultations with local authorities, miners, and community members provided critical insights into the perceived risks and operational practices, ensuring the findings are actionable and relevant at the community level. Fieldwork was conducted from November 2024 to March 2025.

The summary of the key findings is as follows:

1. **Mercury:**
    a. **Soil:** Mercury concentrations were markedly elevated at the Konongo Zongo site in the Ashanti Region. The mean concentration of **56.40 ppm** exceeded the guideline **of 10 ppm** for playground soils by **560 percent.** Other locations, Konongo Odumase (**31.01 ppm)**, Prestea (**30.43 ppm)**, and Dakrupe (**6.02 ppm)**, also exhibited notable contamination.[1]

    b. **Water:** Several water samples surpassed the national limit of **0.001 mg/L** (maximum observed 0.01 mg/L), indicating significant contamination risks to local water bodies and aquatic ecosystems.[2]

    c. **Air:** Ambient mercury vapor concentrations were generally within the **1 µg/m³** standard, except at Wassa Kayianko in the Western Region, where the mean of **1.84 µg/m³** exceeded the limit by **84 percent**. Diurnal variations, higher temperatures, and late-day amalgam smelting contributed to peaks up to **150.20 µg/m³**.

[1] GSA, (2024). Water quality specification for drinking water. GS 175:2024. 6th Edition.

[2] Food and Agriculture Organization (FAO) & World Health Organization (WHO). (1995). Codex General Standard for Contaminants and Toxins in Food and Feed. CODEX STAN 193-1995. https://www.fao.org/fileadmin/user_upload/agns/pdf/CXS_193e.pdf

d. **Fish:** Mercury concentrations in fish were below the **0.5 mg/kg** threshold; however, the limited sample size restricts definitive conclusions.

e. **Food Crops:** Total mercury was detected in some vegetables (e.g., spinach and tomatoes). As only total mercury was measured, methylmercury speciation is required for a robust risk assessment.

2. **Lead:**

a. **Soil:** Mean lead concentrations remained below the **200 ppm** residential soils guideline. Dakrupe recorded the highest mean level of 48.49 ppm (approximately **24%** of the reference threshold) with individual readings up to **3,899 ppm.**[3]

b. **Water:** Lead levels in several samples exceeded the **0.01 mg/L** limit peaking at **0.97 mg/L** in Asiakwa (Eastern Region), where approximately **50%** of samples were above the threshold raising concerns for drinking water safety.

c. **Fish:** Mean lead levels exceeded the 0.3 **mg/kg threshold at** Konongo Zongo and Akwaboso with a **maximum** of **2.80 mg/kg** in Akwaboso, highlighting the need for further risk evaluation.

d. **Food Crops:** Lead was detected in numerous food samples, with pumpkin leaves (under the classification of "vegetable") from the Western North Region recording a maximum level of **3.1 mg/kg**, compared to the **threshold level of 0.1 mg/kg.** Since most food samples were below the respective threshold level for lead, and no clear regional nor crop specific picture could be identified, further testing of different food crops would be needed to monitor potential lead contamination of crops.

3. **Arsenic:**

a. **Soil:** Maximum arsenic levels of **10,060 ppm at Konongo Zongo**; **4265%** above the threshold.

b. **Water:** Total arsenic surpassed **0.01 mg/L at** Konongo Odumase, Nyamebekyere, and Ankobrah**. A maximum level** of **3.30 mg/L**, indicating serious drink water contamination, was found in Konongo Odumase.

c. **Fish:** Most sites showed mean arsenic levels above **the 0.1 mg/kg threshold**, peaking at **3.09 mg/kg** in the Konongo Zongo site. Speciation analyses are necessary to determine toxicology risk.

d. **Food Crops:** Numerous food samples exceeded arsenic thresholds. Arsenic speciation of different food crops is essential for accurate exposure assessment.

4. **Cadmium:**

[3] U.S. Environmental Protection Agency. (2024, January 17). Updated residential soil lead guidance for CERCLA sites and RCRA corrective action facilities. Office of Land and Emergency Management. https://semspub.epa.gov/work/HQ/175347.pdf

a. Cadmium was generally undetectable or at low concentrations in soil. Nonetheless, its cumulative toxicity warrants ongoing surveillance.

Community engagement revealed strong awareness of mercury-related health risks and miners' willingness to engage in sustainable mining practices. The socio-demographic profile is dominated by traditional miners and farmers with modest educational attainment levels and reliance on market sourced foods. This dependence highlights the urgency for robust food security strategies.

The study calls for coordinated, long-term strategies to mitigate heavy metal pollution and safeguard public health. Key recommendations are to:

a. Capacity building including training local environmental officers in the use of portable analytical tools such as XRF and Jerome analyzers to enhance frequent and reliable data collection.

b. Comprehensive human biomonitoring in high-risk areas, particularly the Ashanti Region, including further analysis like food speciation and a dedicated bioassay sub-study for mixed mercury and arsenic exposures to assess biological impact.

c. Increasing the availability and accessibility of environmental data to support more transparent and evidence-based policymaking.

d. Establish an open-access environmental monitoring database to enhance data transparency and inform policymaking.

Ultimately, a holistic approach that combines technical training, ongoing community engagement, and rigorous policy enforcement is imperative to reduce the health and ecological impacts of heavy metals in ASGM-affected regions.

LIST OF ACRONYMS

AC	Ankobra Community
AK	Akwaboso
AR	Ashanti Region
AS	Asiakwa
As	Arsenic
ASGM	Artisanal and Small-Scale Gold Mining
AV	Average
Cd	Cadmium
CR	Central Region
DA	Dakrupe
EC	European Commission
EPA	Environmental Protection Authority
ER	Eastern Region
EU	European Union
EUR	European Union Regulation
FAO	Food and Agriculture Organization
FDA	Food and Drugs Authority
GIS	Geographic Information System
GPS	Global Positioning System
GSA	Ghana Standards Authority
Hg	Mercury
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
KO	Konongo Odumase
KZ	Konongo Zongo
LA	Lake Amponsah
MAX	Maximum
MESTI	Ministry of Environment, Science, Technology, and Innovation
MIN	Minimum
NY	Nyamebekyere
OS	Osino
Pb	Lead
PR	Prestea
RL	Reporting Limit
SD	Standard Deviation
SR	Savannah Region

TA	Tinga
TSIP	Toxic Site Identification Program
WHO	World Health Organization
WK	Wassa Kanyanko
WNR	Western North Region
WR	Western Region
XRF	X-Ray Fluorescence

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Chapter 1 INTRODUCTION

1.1 Background

The artisanal and small-scale gold mining (ASGM) sector in Ghana is a vital component of the country's economy, providing employment and income for a significant portion of the population. ASGM supports local livelihoods and contributes to national gold production, making the sector a key driver of socio-economic development, particularly in rural communities. However, ASGM Small-scale mining activities, particularly water mining (called *changfan* locally) and land mining (called *galamsey* locally) often results in the pollution of water bodies and the removal and destruction of vegetative cover and soils (Achina-Obeng & Aram, 2022; Bansah et. Al 2018).

Mercury is frequently used in ASGM due to its tendency to form an amalgam with gold. The amalgam can be burned, releasing the mercury into the environment, and leaving behind gold. Mercury-related practices, such as whole ore amalgamation, amalgam burning either in open or in enclosed areas, and direct addition in trammel, are often used in the ASGM sector, each carrying their own risk of increasing mercury exposure to workers, their families, their communities, and the environment (Mantey et al., 2020).

In addition to mercury, ASGM activities mobilize naturally occurring Cd, Pb, and As from gold-bearing rock formations. These elements are released during ore crushing, grinding, and sediment washing, and subsequently accumulate in surrounding soils, rivers, and food crops. Chronic exposure to these metals poses serious public-health threats. For example, arsenic interferes with cellular respiration and is a proven carcinogen of the skin, bladder, and lungs; cadmium accumulates in the kidneys, precipitating tubular dysfunction, bone demineralization and cardiovascular complications; and lead disrupts heme synthesis and neurodevelopment, causing cognitive deficits in children and hypertension in adults (Jomova et al., 2024; Mitra et al., 2022). Food-chain transfer compounds the risk: root and tuber crops such as cassava, cocoyam, and plantain readily absorb and store these elements from contaminated soils, elevating dietary intake among farming communities (Bortey-Sam et al., 2015; Nkansah et al., 2021; Obiri et al., 2006; Opoku et al., 2024).

The ecological consequences are equally alarming. The presence of Hg, Cd, Pb, and As in soils and water bodies has been shown to disrupt aquatic ecosystems, reduce biodiversity, and compromise the fertility of agricultural lands (Khushbu et al., 2022.; Hama Aziz et al., 2023). These impacts threaten food security and the sustainability of local economies dependent on farming and fishing. Moreover, the persistence of these heavy metals in the environment means their toxic effects may linger for decades even after mining activities have ceased (Opoku et al., 2024).

The improper handling and disposal of waste in ASGM activities results in direct exposure to heavy metals among miners, as well as indirect exposure to surrounding communities through air emissions and contaminated water and food supplies. Mercury associated with ASGM operations remains of highest concern due to its neurotoxicity. When mercury is released into the environment, it can contaminate soils, waterways, and food sources, leading to serious ecological and human health concerns. This presents significant risks, including neurological disorders, respiratory problems, and developmental impairments, particularly among vulnerable populations such as children and pregnant women. Other heavy metals of concern that could result from ASGM activities include lead, cadmium, and arsenic.

The contamination of natural ecosystems due to heavy metals also disrupts biodiversity and degrades land and water resources essential for agriculture and fishing, thereby threatening food security and local economies. The persistence of some of these heavy metals, such as mercury, in the environment further exacerbates these challenges, making it imperative to assess the extent of its impact and develop effective mitigation strategies.

Despite national efforts stemming from international initiatives such as Ghana's commitment to the Minamata Convention to reduce mercury use, there remains a gap in comprehensive data on the extent of heavy metals contamination and its socio-environmental impacts.

This initiative underscores the urgency of addressing heavy metals pollution in ASGM and highlights the need for multi-stakeholder collaboration, including government agencies, environmental organizations, mining communities, and international partners, to ensure a balanced approach that supports both economic livelihoods and environmental sustainability. This Heavy Metals Impact Assessment provides critical data to inform policy decisions, strengthen regulatory frameworks, and develop sustainable alternatives mitigation actions in heavy metals pollution in gold mining. The findings support interventions aimed at protecting vulnerable populations, promoting environmentally responsible mining practices, and enhancing Ghana’s efforts in mitigating environmental impacts.

1.2 Objectives

The general objective of the study was to assess heavy metals pollution in eleven ASGM sites in six mining regions of Ghana through analysis of environmental media (e.g., air, soil, water, fish, and food crops). The heavy metals selected for evaluation were mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As).

Specific objectives were:

a) Identify and establish the geographical limits of each site to be evaluated; sites could be either active or inactive mining areas.
b) Determine the degree of heavy metals contamination in each identified site, including air (only for Hg), soil, surface water bodies & bore holes, fish, and food crops.
c) Analyze data and prioritize sites most affected by each heavy metal selected according to the Blacksmith and Mercury Contamination Index.
d) Increase our understanding of heavy metal contamination from mining and its interaction with the food system.

1.3 Scope of the Study

The study aimed to assess environmental exposure to mercury, lead, cadmium, and arsenic in the study areas.

1.3.1 Environmental Focus:

a) Measurement of concentrations of mercury, arsenic, lead, and cadmium.

b) Sampling of air (only for Hg), water, soil, fish, and food crops (vegetables, fruits, grain, cereals, etc.).
c) Identification of potential contamination sources such as mining activities, agricultural practices, and industrial emissions.
d) Comparison of detected levels with international value reference or threshold limits.

1.3.2 Stakeholder Engagement:

a) Consultations with local authorities, regulatory agencies, and community leaders.
b) Discussions with farmers, traders, and residents to understand potential sources of heavy metal contamination.
c) Engagement with environmental and public health experts for insights on risk assessment and mitigation strategies.

1.3.3 Household Survey:

a) Assessment of dietary habits and sources of food and water.
b) Evaluation of community awareness regarding heavy metal contamination and its health risks.

Chapter 2 AREA DESCRIPTION

Ghana has been a leading gold producing country for over a millennium (Hilson, 2002). Today, the labor-intensive artisanal and small-scale gold mining (ASGM) sector employs the majority of gold workers and accounts for more than 40% of Ghana's export revenues (Basu et al., 2015). In 2018, national gold output reached 130.5 tons, with ASGM operations contributing 43.1% of the total sum (Saim, 2021). While ASGM operations occur nationwide, the scale and environmental impacts vary by region. Figure 2.1 maps the principal ASGM zones in Ghana. The study focused on the regions which are most acutely affected by mercury pollution from extensive mining: **Ashanti, Western, Western North, Eastern, Savannah, and Central.** The following sections synthesize literature on heavy metals contamination across these regions.

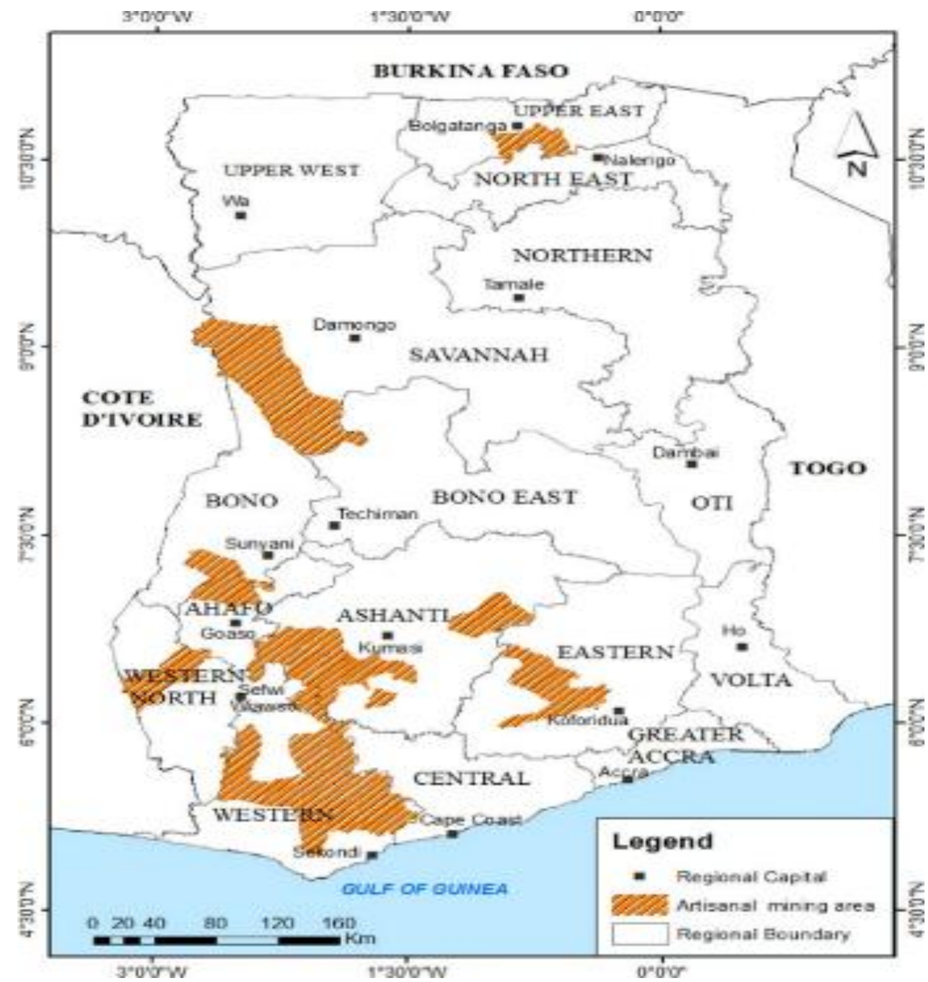


Figure 2.1: Map showing ASGM areas in Ghana (Takyi et al., 2021)

2.1 Ashanti Region

The Ashanti Region, a major hotspot for illegal mining activities in Ghana, is facing a serious threat to river water quality due to heavy metals leaching from mining activities (Obiri et al. 2016; Boateng, 2018; Duncan, 2020; Anoyege & Alatinga, 2024). According to Ofosu-Asiedu et al. (2013), the Konongo-Odumasi Municipality is highly exposed to copper, mercury, lead, and cadmium in surface and groundwater. Anang et al. (2023) identified Kumasi's Aboabo and Wiwi rivers as significant sites of mercury contamination with mercury levels in the Anloga section of the Aboabo River exceeding WHO-recommended limits, mostly due to electronic waste processing and dumping. Nartey et al. (2019) warn that although ASGM normally takes place in remote areas, it still poses a significant risk of mercury contamination to urban drinking water sources such as the Owabi Reservoir which supplies Kumasi.

Figure 2.2: Map showing Districts in Ashanti Region (Ghana LGS, n.d.)

2.2 Western Region

A study by Ovadje et al. (2021) revealed that median urinary mercury levels in miners from four selected unlicensed sites in Western Region were approximately three times greater than those from five licensed sites, identifying distinct pollution hotspots (Ovadje et al., 2021). Mantey et al. (2020) recorded elevated measurements of mercury in sludge/slurry and surface water/drainage samples at various *galamsey* sites across the Tarkwa Nsuaem, Amenfi East, and Prestea Huni Valley districts (Mantey et al., 2020).

The Ankobra and Tano river basins pass through gold, manganese, and diamond mining villages in the Western Region. The Ankobra river basin receives inflow from a network of streams and rivers, the majority of which run through major agricultural lands and areas of heavy mining activity, including a manganese mine at Nsuta and seven large-scale gold mines scattered around the Prestea, Tarkwa, Iduaprim, and Damang areas (Akabzaa et al., 2009). Also dangerous is the runoff from dispersed ASGM operations along the basin (Kortatsi, 2007). Several large fishing settlements, such as Sanwoma and Jaway Wharf – Ellenda, rely primarily on fish from the Ankobra and Tano rivers, respectively however mercury, arsenic, and lead pollution levels surpass recommended levels at both basins (Awuah, 2016; Baah, 2000; Adimado & Baah, 2002).

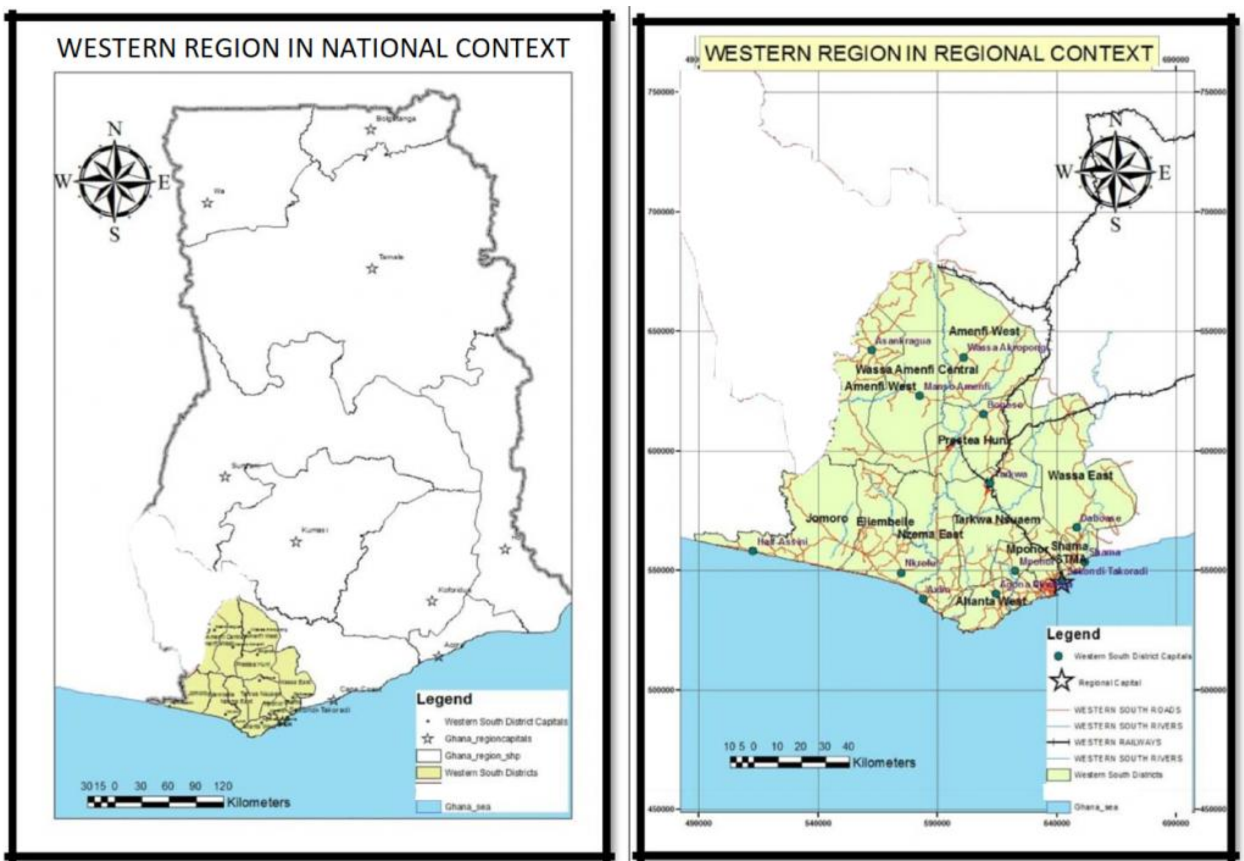


Figure 2.3: Maps of Western Region (Western Region Co-ordinating Council, 2022)

2.3 Western North Region

Higher mercury levels were significantly associated with ASGM-related activities such as amalgam burning and sucking of excess mercury (Afrifa et al., 2017). A study by Attiogbe et al. (2020), which assessed heavy metal levels as well as physical parameters in Lake Amponsah, reported mean mercury concentrations of 0.0053 mg/L in water samples, exceeding the Ghana EPA threshold of 0.001 mg/L. Arsenic and cadmium levels were also elevated, with a reported mean arsenic concentration of 0.311 mg/L as compared to the Ghana EPA threshold of 0.01 mg/L, and a reported mean cadmium concentration of 0.037 as compared to the Ghana EPA threshold of 0.005 mg/L (Attiogbe et al., 2020). Though region-specific data on cadmium and arsenic are limited, studies across Ghana confirm their presence in mining-affected environments (Miller et al., 2015).

Figure 2.4: Map of Western North Region (Ghana LGS, n.d.)

2.4 Eastern Region

Unregulated activities have resulted in the pollution of water bodies such as the Birim River Basin (Alhassan et al., 2022). Atiwa West has numerous domestic sources of water, including rivers, streams, and groundwater. Small-scale mining activities, particularly water mining (called *changfan* locally) and land mining have increased significantly along the Birim River in the Atiwa district since 2010 (Bansah et al., 2018). In previous studies by Asamoah (2012) and Gyampoh (2013), mercury residues were detected in both sediments and rivers located in areas known for ASGM activities. In their operations, the miners use automated dredging equipment mounted on mobile rigs and dump mounds of sand into the river to aid in their activities (Oduro et al., 2012). Currently, ASGM activities are found in areas such as Efisa, Adadientem, Akyem Adukrom, Asikam, Obronikrom, Osino, and Abomoso located in the Akyem Abuakwa District of the Eastern region (Figure 2.5).

Figure 2.5: Map showing Districts in Eastern Region (Ghana LGS, n.d)

2.5 Savannah Region

Tinga is situated in the Bole-Bamboi District of the Savannah Region and falls under the Guinea Savannah agro-ecological zone. Areas along the black volta including Tinga, Kuri, Bombiri, Dakrupe, and Seripe, has shown potential for gold deposits highlighting the area's long-standing status in Ghana's ASGM sector. Mercury contamination is widespread in Tinga, with water sources often having quantities above WHO guidelines (Cobbina et al., 2015). Emerging *galamsey* activities in districts like West Gonja, Central Gonja, and Sawla-Tuna-Kalba (Figure 2.6) in the Savannah Region are impacting local ecosystems and natural resources.

Figure 2.6: Map of Districts in Savannah Region (Ghana LGS, n.d.)

2.6 Central Region

In the Central Region, ASGM has significantly increased environmental pollution with heavy metals, especially in communities along the Dunkwa-on-Offin River. According to Kpan et al. (2014), concentrations of Hg and Pb in soil and water samples from Dunkwa revealed levels of lead and mercury exceeding EPA guidelines. The broader impacts of ASGM activities in the region also include destruction of farmlands, pollution of rivers, and potential long-term water insecurity.

Figure 2.7: Map of Districts in Central Region (Ghana LGS, n.d.)

Chapter 3 METHODOLOGY

The methodological framework enabled a systematic evaluation of ASGM's impacts on public health and the environment by identifying the presence, contamination levels, and potential health impacts of mercury, lead, cadmium, and arsenic, with a particular focus on their pathways into the food chain, across six regions of Ghana (Figure 3.1). The study adopted an integrative approach that combined environmental sampling with stakeholder and community engagement. Key activities included training the field research team, conducting desk reviews, performing on-site observations, and obtaining real-time mercury vapor measurements. Comprehensive sampling and analysis of soil and other media for all four heavy metals were conducted alongside structured community consultations. This methodology facilitated the identification of contaminated sites, enabled risk assessments, and provided data on heavy metal concentrations and associated health hazards in the study areas.

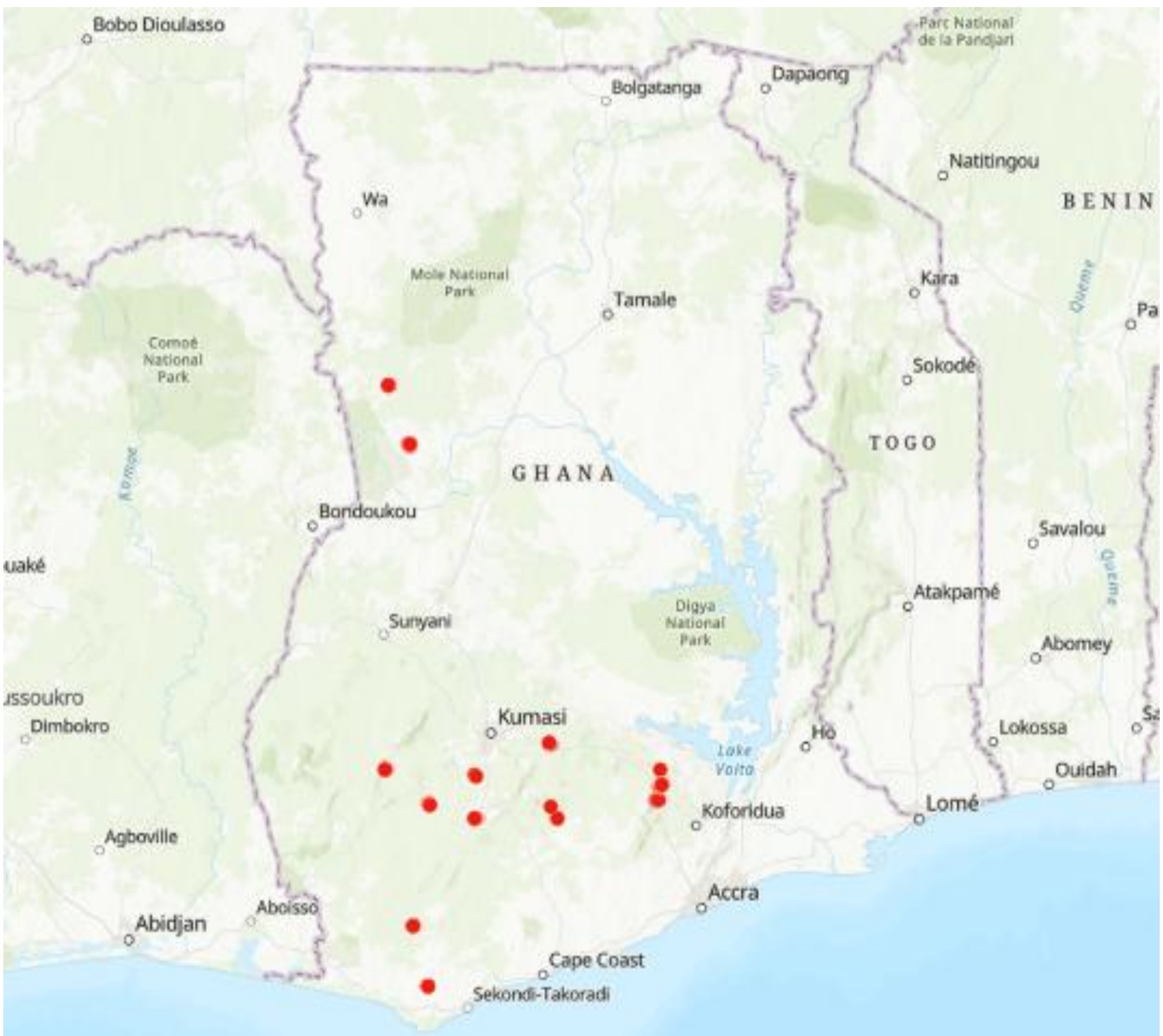


Figure 3.1: Map Indicating Study Areas

3.1 Desk Review

The desk review phase consisted of an analysis of existing data and information sources. This process informed a preliminary map of the study area, identifying potential hotspots of contamination based on historical and current information.

Researchers used a variety of sources, including:

- Toxic Sites Identification Program (TSIP): TSIP provides detailed information on contaminated sites in low- and middle-income countries and identifies those that pose the greatest threat to human health (www.contaminatedsites.org).
- Environmental impact assessments: Previous studies offer important baseline data and highlight areas of known contamination.
- Public health reports: Local health statistics indicate areas with higher incidences of diseases associated with heavy metal exposure.

3.2 Site Identification and Prioritization

The initial desk review resulted in a list of ASGM sites for potential assessment, which were then prioritized based on their accessibility, history of mercury usage, and proximity to agricultural and residential areas. These criteria ensured that high-risk sites were targeted, with a particular focus on those where contamination could affect food crops or markets selling local produce. Site selection was also based on logistical feasibility, given regional infrastructure constraints, ensuring that each visit could be completed within an allocated time frame.

3.3 Toxic Sites Identification Program (TSIP) Training

This activity aimed to train the Ghana Environmental Protection Agency (EPA) and the Ministry of Environment Science Technology and Innovation (MESTI) on skills necessary for the Heavy Metals Impact Assessment Project. In attendance were 2 representatives from MESTI, 10 representatives from EPA and the remaining were the Pure Earth field team. The training included a two-day round table with expert presentations on mercury contamination (Figure 3.2) and a field trip to an ASGM site in Kyebi (Figure 3.3). Key topics covered assessment methodologies, equipment demonstrations, stakeholder engagement, and intervention strategies for vulnerable populations. The training emphasized accurate data collection and proper sampling techniques.

Figure 3.2: TSIP Roundtable Training Session

Figure 3.3: Field Session during the TSIP Training

3.4 Data Collection Techniques

The data collection strategy formed the core of the assessment methodology and was designed to capture comprehensive information on the selected heavy metals including contamination extent, environmental distribution, and potential pathways into the food chain. This multi-faceted approach combined observational methods, instrumental measurements and analysis, geospatial data collection, socio-economic surveys, and stakeholder engagement. Steps included:

1. **Direct Observation:** Trained field researchers conducted systematic site walkthroughs, noting active mining practices such as ore extraction methods and the use of chemicals like mercury. They also documented waste disposal methods, focusing on tailings (mining waste products) and wastewater management, while observing any visible contamination. Additionally, they assessed environmental degradation by evaluating deforestation, soil erosion, and water turbidity, providing a comprehensive understanding of the ecological impacts of mining activities.

2. **In-Situ Measurements:** Real-time rapid measurements of mercury levels were conducted using a portable X-ray fluorescence (XRF) analyzer for determination of heavy metals concentration in soil samples and the Jerome device for mercury vapor analysis. The XRF analyzer is a handheld, non-destructive analytical instrument that determines the elemental composition of materials by measuring the characteristic secondary X-rays emitted when a sample is excited by a primary X-ray source. The Jerome device detects and measures mercury vapor in the air. The team adhered to GPS coordination protocols, recording precise locations of each measurement to map mercury concentrations spatially (Figure 3.4).

Figure 3.4: Research Team Using the XRF, Jerome, and GPS Devices

3. **Stakeholder engagement:** Informal interviews with ASGM workers, residents, and authorities were a key component of the assessment, providing additional insights into the perceptions of heavy metal contamination risks, handling practices, and the impact of mining activities on agriculture and public health.

4. **Documentation and Field Notes**: Detailed field notes were maintained, recording all relevant observations. This included noting conditions specific to each site, such as proximity to water sources, storage conditions for mercury, and any additional hazards identified.

3.5 Sampling Strategy

The sampling strategy which included the UNIDO and Pure Earth, 2019 methodology was designed to ensure that collected samples were representative, uncontaminated by the sampling process, and suitable for accurate analysis. This section outlines the approaches for soil, water, food crops, and fish sampling, each tailored to the specific characteristics of the medium and the contaminants of interest.

3.5.1 Soil Sampling

Soil sampling was conducted using a systematic approach similar to Li et al., 2017, which allowed for comprehensive coverage of the study area while minimizing bias in sample selection. Key aspects of the soil sampling methodology included:

- Sampling depth: Samples were collected from the 0–15 cm depth range.
- Samples were collected in the form of a grid pattern for assessable areas in order to cover the surface area for each site.
- The samples homogenized prior to testing.
- To validate data from the XRF measurements, at least 8 readings were taken from each of the samples to be sent to the laboratory for correlation with the laboratory's ICP-MS results.
- Sample handling: Samples were stored in pre-cleaned, pre-tested, labeled sampling bags (Figure 3.5) and kept cool during transport to minimize any chemical changes.

Figure 3.5: Soil Samples Stored in Pre-labeled Sample Bags

3.5.2 Water Sampling

Water sampling was designed to assess both upstream and downstream contamination and in surface water and groundwater. Water samples were collected at predetermined intervals along water bodies, with sampling points chosen to capture potential variations in contamination (i.e., upstream and downstream of mining activities). Samples were collected from the middle of the stream where possible, at mid-depth. The samples were preserved with nitric acid and stored in plastic containers (pretreated bottles from the lab) to prevent changes in the sample's composition until lab analysis (Figure 3.6).

Figure 3.6: Water Samples in Bottles Filled with Nitric Acid

3.5.3 Food crop sampling

Dominant crop species were identified through socio-economic surveys and field observations. Samples were collected from multiple points within agricultural areas, considering factors such as proximity to contamination sources. Both edible portions (e.g., grains, fruits) and non-edible portions (e.g. leaves) were collected to assess metal translocation within plants. The different types of food were categorized into food groups, and the analysis of the results will be presented by both group and food.

Sample preservation:
Plant samples were cleaned of soil particles, dried at low temperature (<40 °C) to prevent or reduce the advancement of the process where heavy metals (e.g., mercury) turn into a gaseous or vapor state, potentially escaping into the air, and stored in sampling bags.

3.5.4 Fish sampling

Sampling was conducted using methods that comply with local regulations and ethical considerations. Multiple fish (7) from each site were collected to account for potential variations in metal accumulation due to factors such as size and age. Fish samples were measured for total length and weighed as shown in Figures 3.7 and 3.8, respectively. Using these factors, the age of the fish was estimated for further analysis. Fish samples were placed in sample bags and stored in a cold box with ice pending lab analysis.

Figure 3.7: Measuring Fish Sample Length and Weight

3.6 Laboratory Methodology

This section will provide a detailed description of the sample analyses performed by the SGS laboratory in Tema, Ghana. For quality assurance, for every batch of 10 samples processed, one duplicate sample (a repeat analysis of a randomly selected sample to assess precision) and one blank sample (to monitor potential contamination) were systematically inserted into the analytical sequence. This ensured consistent evaluation of method reproducibility and detection of procedural interference.

3.6.1 Water Samples
Test: Major cations & trace metals
Method: APHA 3120, US EPA 200.8, and US EPA 200.7
Equipment: ICP-MS & ICP-OES

Sample Preparation
For dissolved metals, samples were filtered through a 0.45-µm filter and preserved with drops of HNO_3 to pH < 2 for ICP-MS and ICP-OES analysis.

For total metals, 50 mL sample was treated with a 1:1 mixture of concentrated hydrochloric acid (HCl) and nitric acid (HNO_3) and digested on a pre-heated hot block at 110 °C for 2 hours and 30 minutes. After digestion, the mixture was cooled and diluted to the 50 mL mark with deionized water. Metal concentrations in the samples were determined using a Nexion 2000P ICP-MS and AVIO 500 ICP-OES after calibration and tuning of the instrument. Quality control measures, including method blanks, replicates, and certified reference standards, were implemented to ensure the accuracy and precision of the results. The concentrations obtained were expressed in **mg/L**.

3.6.2 Soil and crops
Test: Metals in soil and crops
Method: US EPA 3050, US EPA 200.8

Sample Preparation and Analysis

Pre-analytical processing of the food samples: All samples were handled in strict accordance with SGS's standard operating procedures. The food samples were meticulously rinsed with deionized water prior to peeling in order to ensure the removal of any surface debris or dust. Thereafter, the samples were dried using an air-drying method and subsequently milled. Following this process, the samples were digested and analyzed. In order to avoid any potential interference with analyte concentrations and to preserve the integrity of the samples, no chemical washing agents were used.

A 2.0-gram portion of the dried sample was weighed into a 50 mL digestion tube, followed by the addition of 2.5 mL of concentrated nitric acid (HNO_3) and 2.5 mL of concentrated hydrochloric acid (HCl). The mixture was heated on a pre-heated hot block at 110 °C for 40 minutes. After cooling, 10 mL of deionized water was added, and the sample reheated for an additional 20 minutes. The digested solution was then cooled and diluted with deionized water to a final volume of 50 mL. Metal concentrations in the samples were determined using a Nexion 2000P ICP-MS and AVIO 500 ICP-OES after calibration and tuning of the instrument. Quality control measures, including method blanks, replicates, and certified reference standards, were implemented to ensure the accuracy and precision of the results. The concentrations obtained from ICP-MS, initially expressed in mg/L, were converted to mg/kg using the formula:
Final concentration (mg/kg) = (ICP-MS result (mg/L) × 50 ÷ 2) × Moisture Factor,
where 50 mL represents the final digestion volume, 2 g is the sample weight, and the moisture factor accounts for variations in sample moisture content.

3.6.3 Fish samples

Test: Metals in fish
Method: US EPA 200.3, US EPA 200.8

Sample Preparation and Analysis

A 2.5-gram portion of fish tissue was subjected to a multi-step acid digestion process to prepare it for heavy metal analysis. Initially, the sample was treated with 5 mL of concentrated nitric acid (HNO_3) and heated at 110 °C until dissolution. After cooling to room temperature, 2.5 mL of HNO_3 was added, and the mixture was heated until the solution turned brown. Following this, 1 mL of HNO_3 was added, and heating continued until the volume reduced to 2.5 mL. Subsequently, 1 mL of hydrogen peroxide (H_2O_2) was added, and heating proceeded until the volume again diminished to 2.5 mL. This cycle of adding HNO_3, heating, and then adding H_2O_2 was repeated, with each cycle aiming to further digest the tissue until 5 mL of H_2O_2 were added. After the final digestion step, 1 mL of hydrochloric acid (HCl) was added, and heating continued until the solution reduced to 2.5 mL. The mixture was then cooled and diluted to the 50 mL mark with deionized water.

Metal concentrations in the samples were determined using a Nexion 2000P ICP-MS after calibration and tuning of the instrument. Quality control measures, including method blanks, replicates, and certified reference standards, were implemented to ensure the accuracy and precision of the results. The concentrations obtained from ICP-MS, initially expressed in mg/L, were converted to mg/kg on wet weight basis using the formula:
Final concentration (mg/kg) = (ICP-MS result (mg/L) × 50 ÷ 2.5),

where 50 mL represents the final digestion volume, 2.5 g is the sample weight, and the moisture factor accounts for variations in sample moisture content.

3.6.4 Reporting limits

The reporting limit (RL) is the lowest quantifiable reporting limit that can be achieved under ordinary conditions. Table 3.1 shows the RLs used for this study.

Table 3.1: Reporting limits (RLs) (as determined by the SGS laboratory)

Elements	Water (mg/L)	Soil (mg/kg)	Food (mg/kg)	Fish (mg/kg)
Mercury (Hg)	0.0001	1	1	0.5
Lead (Pb)	0.0001	1	0.1	0.5
Arsenic (As)	0.0005	2	0.1	2
Cadmium (Cd)	0.0001	0.3	0.3	0.5

Results below reporting limits are given as <RL. For further statistical analysis, reporting limits results were divided by the square root of two.

3.7 X-ray fluorescence (XRF) analyzers

The primary screening instrument employed for the study was a portable X-ray fluorescence (XRF) analyzer. The XRF analyzer is a valuable screening device for this type of study because it has good sensitivity (a low rate of false negatives and accurate detection of true positives with detectable lead). The protocol stipulated the method for preparing each item for testing and the number of XRF readings required for each medium. The samples were analyzed with a Thermo Scientific Niton XL3T XRF and a Vanta XRF analyzer, employing the "Soil" mode for the Thermo Scientific Niton XL3T XRF. The testers were instructed to regularly verify the accuracy of the XRF by comparing its readings with those of the provided "standard" samples, which had known lead concentrations.

The results were subsequently subjected to statistical analysis. The minimum, maximum, quartile, and median levels of lead in the various media were determined. Eighty percent of the XRF results fell below the XRF's lower limit of detection (LOD). Consequently, given the skewed distribution of the data to the left, we have opted to report median values rather than mean values.

3.8 Data Analysis

For each metal and sample type (e.g., soil, water, food crops, and fish), basic descriptive statistics of metal concentration were calculated using Microsoft Office Excel, including mean, median, standard deviation, and range. These statistics provided an initial overview of contamination levels and variability across the study area. Histograms were created to visualize the distribution of metal concentrations, helping to identify outliers and general trends.

ArcGIS was used to generate surface maps of metal concentrations from point sampling data. This geostatistical approach accounts for spatial autocorrelation, providing more accurate estimates of contamination levels between sampling points. The resulting maps offer a visual representation of contamination patterns across the study area.

3.8.1 Reference values

To assess the risk of results from environmental samples, threshold limits carry more legal weight compared to guidance, review, or reference values. While threshold limits are often enforceable standards set by regulations, the others serve primarily as advisory benchmarks to support risk assessments.

To compare the results of this study, national Ghanaian reference values, where possible, were used. For Ghana, reference values were available for air and water (GSA, 2024).

Otherwise, we identified values suggested by other authorities and regulatory agencies:

- Maximum levels of contaminants by the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) (FAO & WHO, 1995)
- Residential soil guidance values by United States Environmental Protection Agency (US EPA, 2024)
- German review values for the soil-human pathway for housing areas and children's play areas. Since children were observed playing within contaminated sites, we applied those values. The soil level for lead is identical with the revised US EPA value (BMUV, 2021).
- European Commission Regulations on maximum levels for certain contaminants in food (EU Commission, 2023)
- China Standards for Maximum Levels of Contaminants (USDA, 2018)

Table 3.2: Reference values for air, water, and soil (reporting/guidance values)

	Air	**Water (mg/L)**	**Water (mg/L)**	**Soil for residential areas (ppm)**	**Soil for housing areas (ppm)**	**Soil for playgrounds (ppm)**
	Ghana	Ghana	FAO & WHO	US EPA	Germany	Germany
Arsenic	15 (ng/m^3)	0.01	0.01	35	50	25
Cadmium	3 (ng/m^3)	0.003	0.003	7.1	20	10
Lead	0.5 (ug/m^3)	0.01	0.01	200	400	200
Mercury	15 ng/m^3 for 24 hrs averaging 1 ug/m^3	0.001	0.001	7.1	20	10

In Ghana, specific national standards for heavy metals in food are not clearly defined in available sources. However, studies conducted in the country often use maximum levels established by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) as reference points. These risk estimations take food consumption patterns into account, and not only the level of contaminants in specific food items. These WHO & FAO reference limits cannot be directly compared with our laboratory results, as in this study the concentrations are expressed in mg/kg per analyzed food item.

To compare the results from this study, which are given in mg contaminant per kg food, one available option is to use the "maximum levels for contaminants in food" from the WHO/FAO or the European Union (EU 2023/915) and if not available, from the Chinese Standards for "maximum levels of contaminants in food", as recommended by the US EPA.

Table 3.3: Maximum Levels (mg/kg) for Contaminants in Fish and Food (as far as available)

	Fish (mg/kg)	Fruit (mg/kg)	Tuber (mg/kg)	Vegetable (mg/kg)	Cereal (mg/kg)	Legume (mg/kg)	Rice mg/kg	Cacao powder mg/kg
	WHO/FAO (+), EU Commission (**), China Standards (###)							
Arsenic	0.1###			0.5###	0.5###		0.2–0.35+	0.5###
Cadmium	0.05**	0.1+	0.1+	0.05–0.2+	0.1+	0.1+	0.4+	2.0+
Lead	0.3+	0.1+	0.1+	0.05–0.3+	0.2+	0.1**	0.5###	0.5###
Mercury	0.5**			0.01###	0.02###		0.02###	

For arsenic, WHO/FAO and EU Commission give limits for inorganic arsenic only.

Chapter 4 STAKEHOLDER ENGAGEMENT

Stakeholder engagement was a crucial aspect of this study, ensuring transparency, collaboration, and informed decision-making. Given the potential environmental and health risks associated with mercury, arsenic, cadmium, and lead contamination in gold mining areas, it was essential to involve key stakeholders, including local communities, government agencies, researchers, and policymakers. Engaging these stakeholders helped facilitate knowledge sharing, enhance awareness, and promote collective action toward addressing the identified risks.

4.1 Identification of Stakeholders

Several stakeholders were engaged during the project, including Ghana Environmental Protection Agency (EPA) staff, chiefs from gold mining communities, gold miners, local community members, leaders at the gold mining sites, media, and medical officers.

4.2 Regional Stakeholder Engagement

From the geographic areas of interest in the study, towns with evidence of mining activity were selected. Community leaders, including the assembly member and committee members, participated in discussions about the area's environmental issues, with particular attention to their perceptions of heavy metal contamination. At the mines, leaders shared their perspectives on mercury contamination and its environmental impact. Additionally, community members, with an emphasis on women, were interviewed to understand their concerns about the effects of contamination on their food and water. The following table shows the selected towns by region.

Table 4.1: Selected Towns for Heavy Metals Assessment

Ashanti (AR)	***Central (CR)***	***Eastern (ER)***	***Savannah (SR)***	***Western (WR)***	***Western North (WNR)***
Konongo Odumase (KO) Konongo Zongo (KZ) Nyamebekyere (NY)	Akwaboso (AK)	Asiakwa (AS) Osino (OS)	Dakrupe (DA) Tinga (TA)	Wassa Kayianko (WK) Ankobra Community (AC)**	Lake Amponsah (LA)

**Only for fish samples

Figure 4.1: Engagement with the Chief at Kyebi King, Eastern Region

This regional stakeholder engagement process was essential in capturing diverse perspectives and ensuring that the study reflected the concerns and experiences of those directly affected by mercury pollution in gold mining areas. Stakeholder engagement was done through various methods including focus group discussions, collaboration with local authorities (chiefs) and government agencies (EPA), and interviews with miners, health officials, and environmental experts. These engagement activities ensured that the concern, insight, and recommendation of relevant parties were captured and considered during the study.

4.3 Regional Stakeholder Engagement Outcomes

Several community members expressed concerns regarding the health risks posed by environmental pollution from mining activities.

Residents from Konongo Zongo expressed concerns about the dust generated by the milling machines and the noise associated with it as mining was taking place right within the community. Most of them requested nose masks to minimize the effect of dust from the mining sites.

In contrast, the residents of Dakrupe a mining community did not voice many complaints likely because almost every family member was directly or indirectly involved in the mining process. This increased involvement may have led to a greater level of acceptance.

The mining site in Tinga is situated about 1.5 hours' drive away from the local community. As a result, the community members did not express complaints about the mining activities impacting them.

At the Ankobra community, the mining process is confined to an area of around 100 square meters, and residents close to the mining center complained about the dust generated during mining operations. The dust is carried by the wind meters away from the mining site particularly affecting those downstream.

At Lake Amponsah, residents raised concerns about the construction of new houses by the miners within the mining area thereby increasing the risk of tenants who will be occupying these houses.

Community members living downstream of the mining site at Wassa Kayianko expressed concerns over their main water source becoming muddy due to mining activities.

At Nyamebekyere, the mining site is located downstream of the town and community members complained of the pollution of their waterbodies due to mining activities. Similar sentiments were shared by residents of Osino and Asiakwa, where the pollution of their water sources has become a significant issue. As a result, these communities rely solely on borehole water for their daily needs in an effort to avoid contamination. In addition to water pollution, the residents in these communities, including Akwaboso, also raised concerns about the impact of mining on their agricultural lands. They reported that mining activities were encroaching upon their farmlands depriving them of their livelihoods.

Health professionals stationed at clinics within some of the mining sites reported high prevalence of respiratory infections, persistent coughing, and various skin diseases among residents. These conditions were frequently observed during routine consultations at outpatient departments. According to the health professionals, regular check-ups were organized for the miners to monitor their health status. Additionally, they confirmed that many miners are engaged in the use of unprescribed substances to enhance their stamina, which is contributing to their health issues.

In a meeting with some local chiefs, they expressed concern over the rate of environmental degradation that was occurring on lands under their jurisdiction. They dissociated themselves from any involvement in illegal mining activities. The chiefs called on government and the EPA to assist in addressing the destruction of their lands. Also, they proposed the conversion of some abandoned mining pits into fish farming sites as a potential solution, aiming to create employment opportunities for the youth.

4.3.1 Community concerns

Several community members expressed concerns regarding the health risks posed by heavy metal contamination, particularly due to the use of mercury. Additionally, dust emissions from milling points at mining sites were identified as a major issue, as these airborne particles travel considerable distances, potentially affecting surrounding communities.

All selected mining sites are near residential areas, with some operations occurring directly within communities such as Konongo, Lake Amponsah, Tinga, and Dakrupe. Health professionals stationed at these sites report a high prevalence of respiratory infections, persistent coughing, and various skin diseases among residents, as evidenced by frequent cases recorded at outpatient departments.

4.3.2 Policy and Regulatory Insights

Engagement with government agencies and policymakers highlighted the need for stricter regulations and enforcement mechanisms to mitigate contamination risks. The engagement with government agencies like the EPA and policymakers highlighted the need for stricter regulations and enforcement mechanisms to mitigate the risks of contamination from mining activities. However, the representatives from the EPA were quick to point out that their monitoring efforts are primarily limited to registered mining companies or groups placed under their supervision. This limitation makes it difficult for the EPA to monitor illegal mining activities, as they do not have the authority to oversee or regulate these operations.

4.3.3 Commitment to Future Engagement

Several stakeholders, especially local authorities and miners showed interest in participating in future studies and monitoring programs to assess long-term impacts and solutions. The engagement also fostered a strong commitment to future collaboration. The chiefs, EPA, community members and miners expressed keen interest in participating in future studies and monitoring programs at assessing long-term impacts of heavy metal contamination.

Chapter 5 RESULTS

This section presents the results for the assessment of mercury in air and mercury, arsenic, cadmium, and lead in soil, water, fish, and food crops.

5.1 Air

The concentration of mercury in the air depends on the degree of volatility of its compounds which is strictly related to the ambient temperature. The quantity of evaporated Hg doubles for each temperature increases of 10 °C (Gworek et al., 2017). According to the Ghana Standards GS1236:2019, the permissible maximum level of mercury in air at locations where burning is used to extract gold is 1 µg/m^3. The following table shows the results of Hg concentration in air samples from areas surrounding the selected sites by the Jerome device.

Table 5.1: Mercury Vapor Concentration (µg/m^3) in Air

Region	Site	# Samples	Mean	Max	Min	SD
AR	KO	60	0.30	2.11	<RL	0.52
	KZ	100	0.49	4.39	<RL	0.78
	NY	90	0.39	4.70	<RL	0.85
CR	AK	100	0.29	1.58	<RL	0.39
ER	AS	83	0.26	4.24	<RL	0.55
	OS	110	0.34	5.87	<RL	0.72
SR	DA	106	0.36	1.73	<RL	0.42
	TA	140	0.46	3.44	<RL	0.52
WNR	LA	80	0.33	3.01	<RL	0.49
WR	PR	76	0.42	3.46	<RL	0.67
	WK	100	1.84	150.20	<RL	15.00

RL = reporting limit, SD = standard deviation, min = minimum, max = maximum
red = above Ghanaian permissible level of Hg in air of 1 µg/m^3

The mean level is below the limit in almost all sites; only the Wassa Kayianko site reports a mean level above the permissible limit with a value of 1.84 µg/m³. It is important to note that the time of day when readings were taken influenced outcomes, as higher ambient temperatures can lead to increased vapor levels and/or the smelting of the amalgams occurred at that time more frequently. Peak individual measurements at Wassa Kayianko reached as high as 150.20 µg/m³. The following graph shows the general distribution of the data.

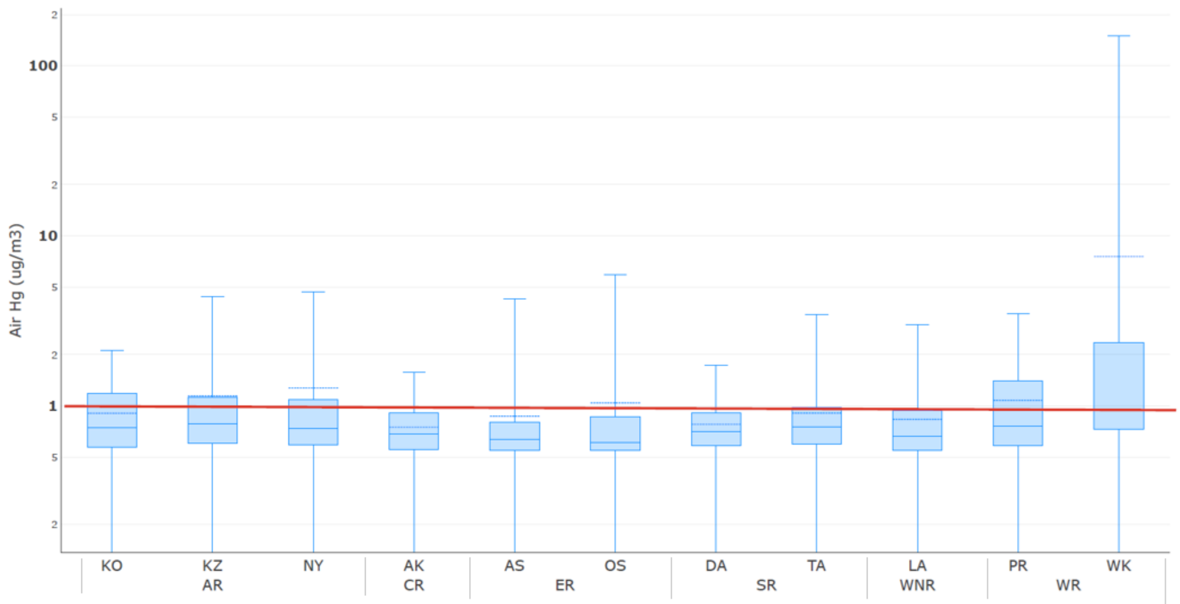


Figure 5.1: Mercury Vapor Distribution per Site

Boxplots, y axis in µg/m3, log scale red line = Ghana permissible level of Hg in air of 1 µg/m^3

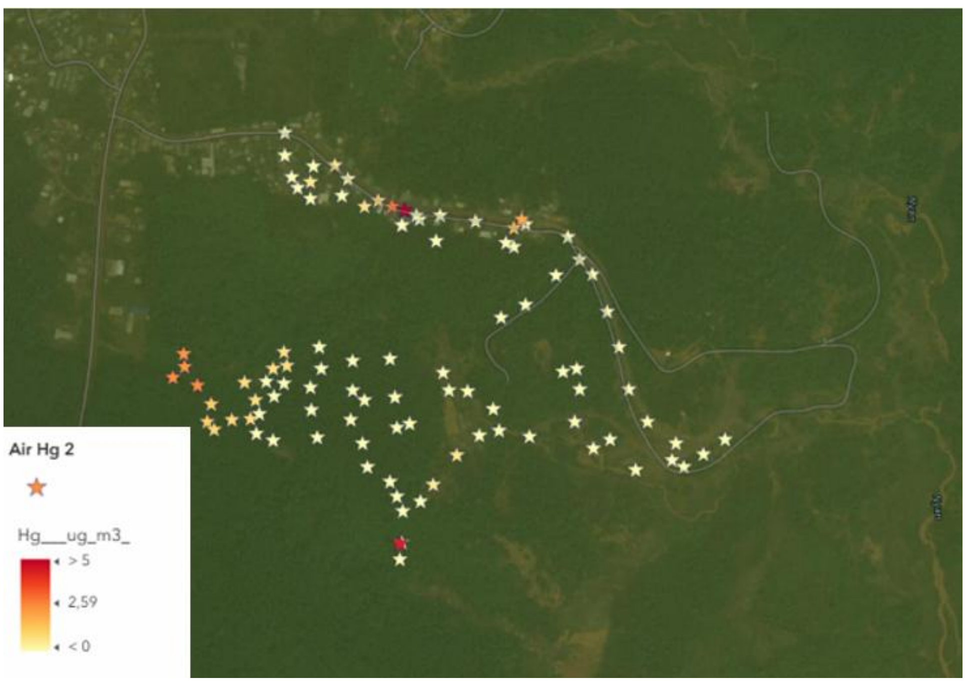
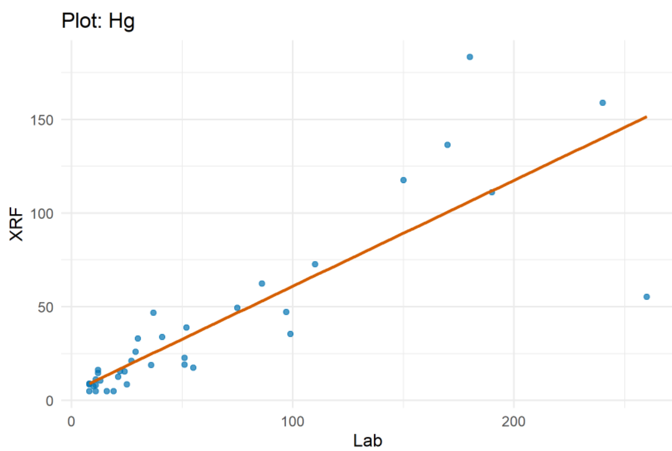


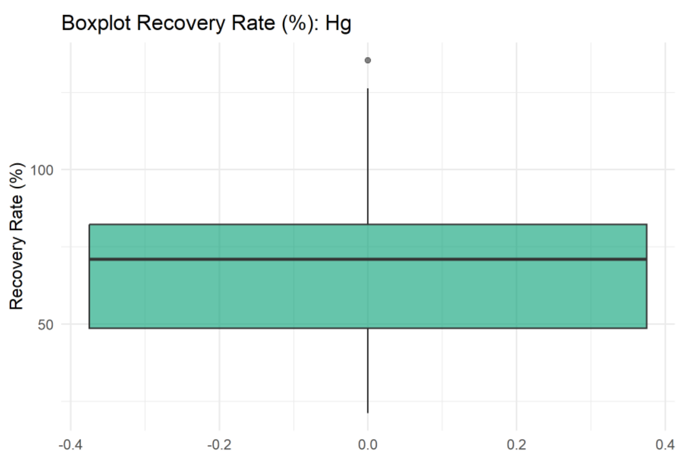
Figure 5.2**: **Mercury Vapor Distribution (µg/m^3) at Wassa Kayianko

5.2 Soil

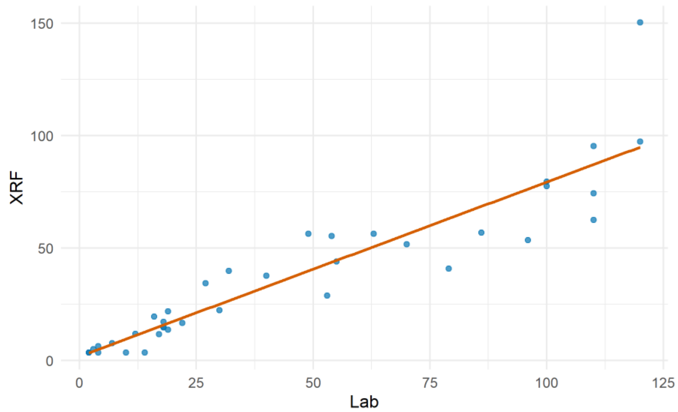
Measurements of the four selected heavy metals were performed using XRF analyzers. 115 confirmatory samples were sent for laboratory analysis using the US EPA 3050 technique to validate the results and determine their correlation. Taking out the <DL and <LOD samples, 37 samples were correlated. The results of this correlation are shown below:

Element	n	Correlation r	r 95% CI (low)	r 95% CI (high)	GM XRF	GM Labor	Ø Recovery Rate (%)	Median Recovery Rate (%)
Hg	37	0.852	0.730	0.922	23.21	35.99	70.82	71.02
Pb	37	0.919	0.847	0.958	23.34	27.23	92.60	81.94
As	37	0.942	0.890	0.970	229.61	225.17	125.81	85.40

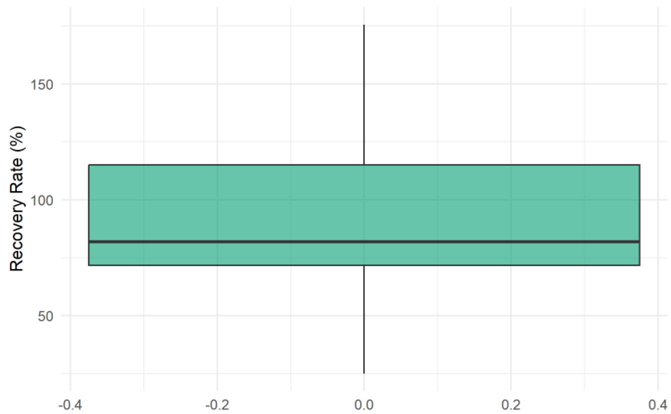




Plot: Pb



Boxplot Recovery Rate (%): Pb



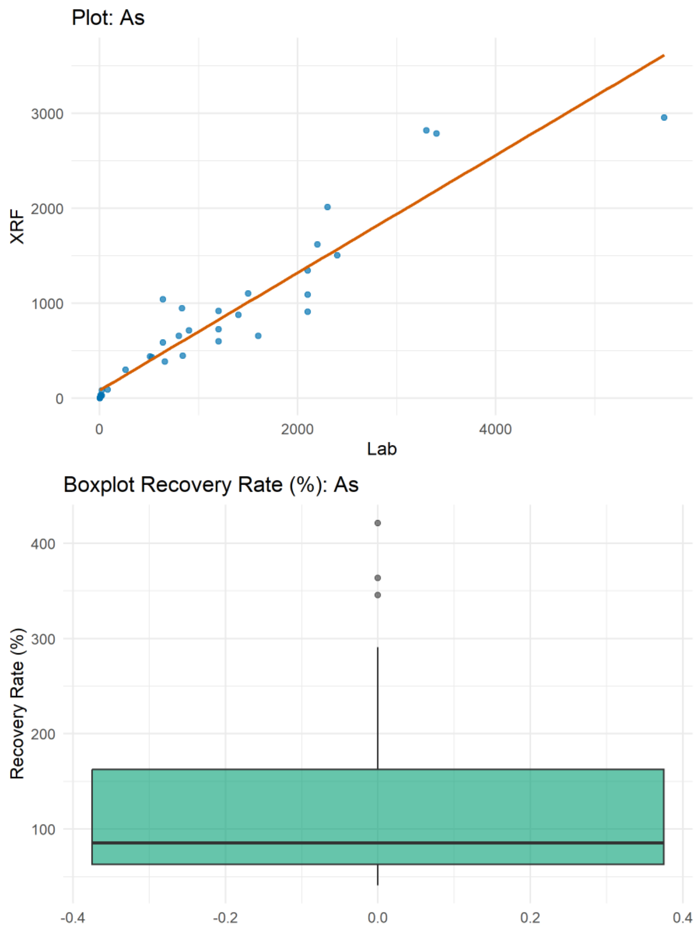


Figure 5.3: Correlation between XRF and Lab Results (Soil)

For these results, we can see Pb is the most reliably measured element by the XRF in both accuracy and correlation. Hg shows reliable correlation, but systematic underestimation requires correction.

As shows strong correlation, but mean recovery >100% suggests overestimation, possibly driven by high outliers of some samples. Despite the limitation of the number of samples for a bigger study, no correction factor will be used.

A total of 1040 readings were taken with the XRF analyzers to determine the concentration of arsenic (As), lead (Pb), cadmium (Cd), and mercury (Hg) in surficial soil across all sites. Of the four heavy metals included in this study, cadmium was the only metal where all results were below the reporting limit (RL). The reference values used to compare the data are: 10 ppm for mercury (German review values for the soil-human pathway for children's play areas; BMUV, 2021), 200 ppm for lead (Residential Soil; US EPA, 2024), and 25 ppm for arsenic (German regulation; BMUV, 2021). The results for Hg, Pb, and As are shown in the following table.

Table 5.2: Heavy Metal Concentration in Soil Samples (ppm)

			Hg (ppm)				Pb (ppm)				As (ppm)			
Region	Site	# Samples	Mean	Max	Min	SD	Mean	Max	Min	SD	Mean	Max	Min	SD
AR	KO	37	31.01	909	<RL	150.84	37.53	250	<RL	50.36	610.38	3110	129	722.92
	KZ	63	56.40	1342	<RL	187.72	22.48	63	<RL	14.21	1066.32	10060	11.0	1741.24
	NY	144	2.74	63	<RL	6.56	14.53	299	<RL	28.12	362.93	3692	<RL	709.85
CR	AK	100	2.00	11	<RL	2.82	5.62	14	<RL	3.63	49.41	478	2.0	67.44
ER	AS	105	0.81	11	<RL	1.00	9.86	25	<RL	6.66	24.62	85	<RL	15.26
	OS	107	0.92	6	<RL	0.94	9.01	46	<RL	7.98	52.83	160	<RL	38.35
SR	DA	110	6.60	291	<RL	30.68	48.49	3899	<RL	370.85	267.77	4510	<RL	542.71
	TA	100	2.27	24	<RL	4.16	4.10	33	<RL	5.65	2.83	10	<RL	2.13
WNR	LA	89	6.21	65	<RL	13.23	35.78	351	<RL	49.02	192.42	3887	<RL	479.83
WR	PR	82	11.73	254	<RL	30.40	36.96	123	<RL	28.49	630.33	3302	41	506.85
	WK	103	7.09	120	<RL	20.00	15.77	605	<RL	59.84	20.28	72	<RL	14.54

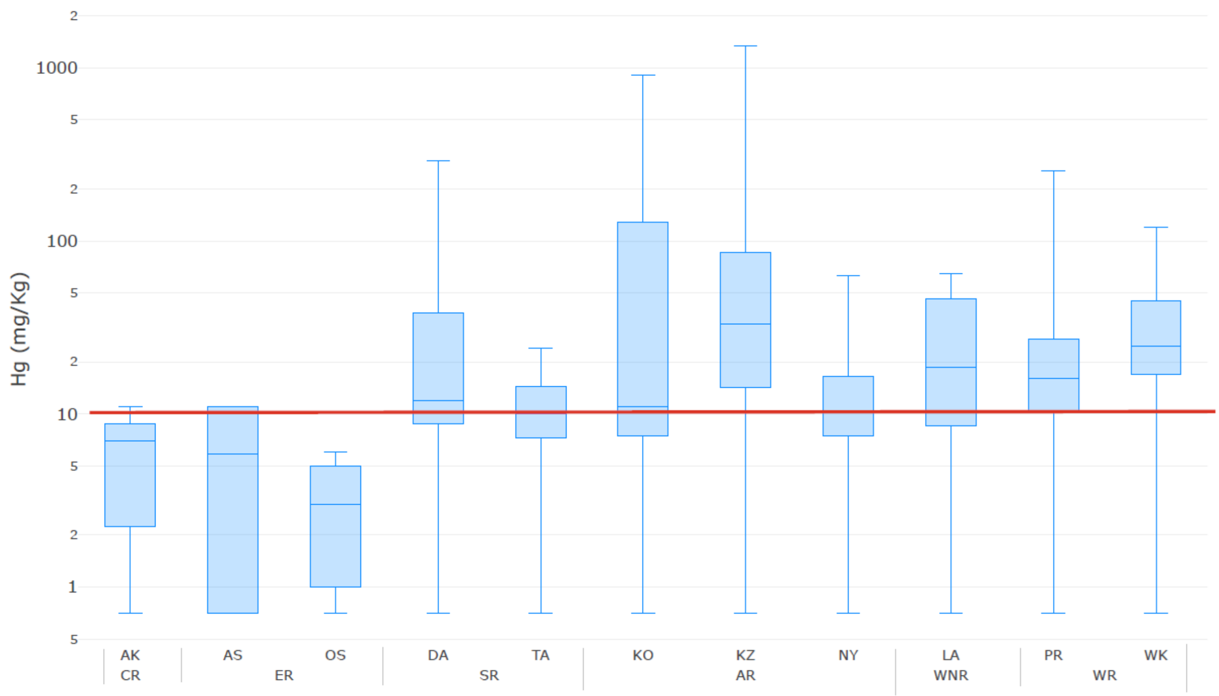
RL = reporting limit, SD = standard deviation, min = minimum, max = maximum
red = above review/guidance values of 10 ppm for mercury (German review values for the soil-human pathway for children's play areas; BMUV, 2021), 200 ppm for lead (Residential Soil Guidance Values and German review values for the soil-human pathway for children's play areas; BMUV, 2021; US EPA, 2024a), and 25 ppm for arsenic (German review values for the soil-human pathway for children's play areas; BMUV, 2021)

For mercury, the average exceeded the reference level at only three sites, two of which are in the Ashanti Region. Konongo Zongo (KZ) is the site with the highest mean mercury concentration, with an average of 56 ppm. Levels of concern were also observed in Konongo Odumase (KO) and Prestea (PR), with mean levels recorded between 11–31 ppm.

The lead concentration averages per site did not exceed the selected reference value. Dakrupe (DA) in the Savannah Region is the site with the highest mean lead concentration at 48 ppm. At the Dakrupe site, the highest individual measurements recorded reached a concentration of 3,899 ppm, which did exceed the reference value.

Of the four heavy metals, arsenic had the highest concentrations compared to the reference level, with most sites reporting a higher value. Konongo Zongo (KZ) is the site with the highest mean arsenic concentration at 1,066 ppm, or more than 40 times the reference value of 25 ppm. The highest concentration was recorded at Konongo Zongo (10,060 ppm), exceeding the threshold level by an astounding 4265 percent.

The distribution of the data compared to the reference values in each contaminant can be seen in Figure 5.3.


Hg (mg/Kg)
2
1000
5
2
100
5
2
10
5
2
1
5
AK
CR
AS
OS
ER
DA
TA
SR
KO
KZ
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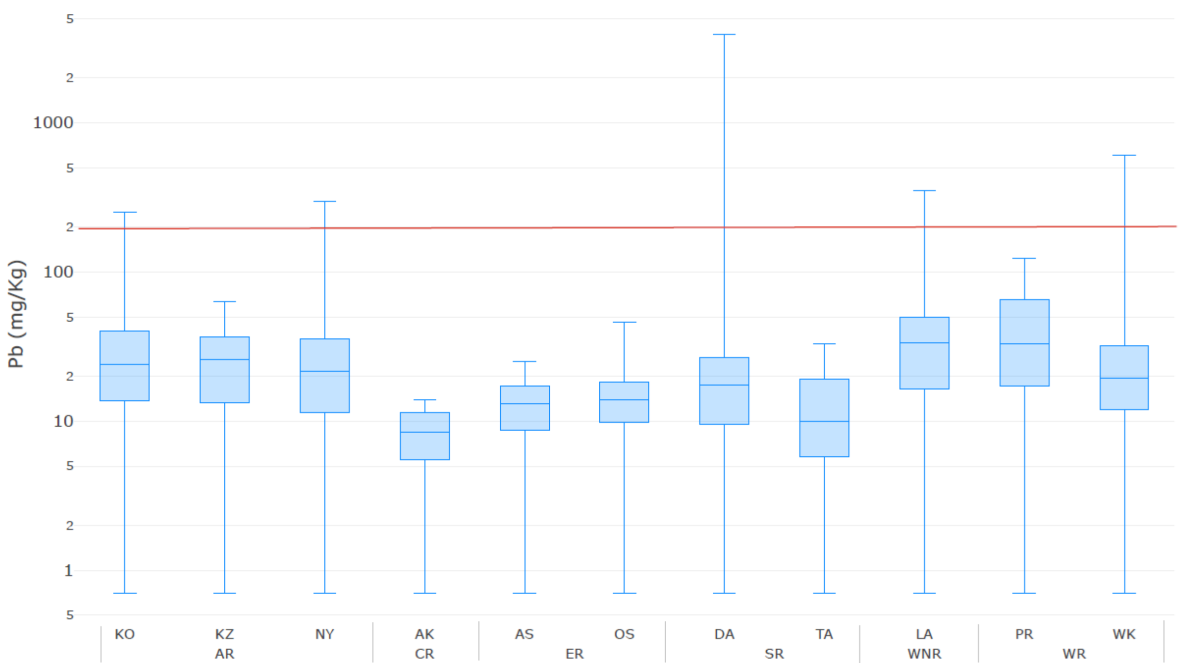
LA
WNR
PR
WK
WR


Pb (mg/Kg)
5
2
1000
5
2
100
5
2
10
5
2
1
5
KO
KZ
NY
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AK
CR
AS
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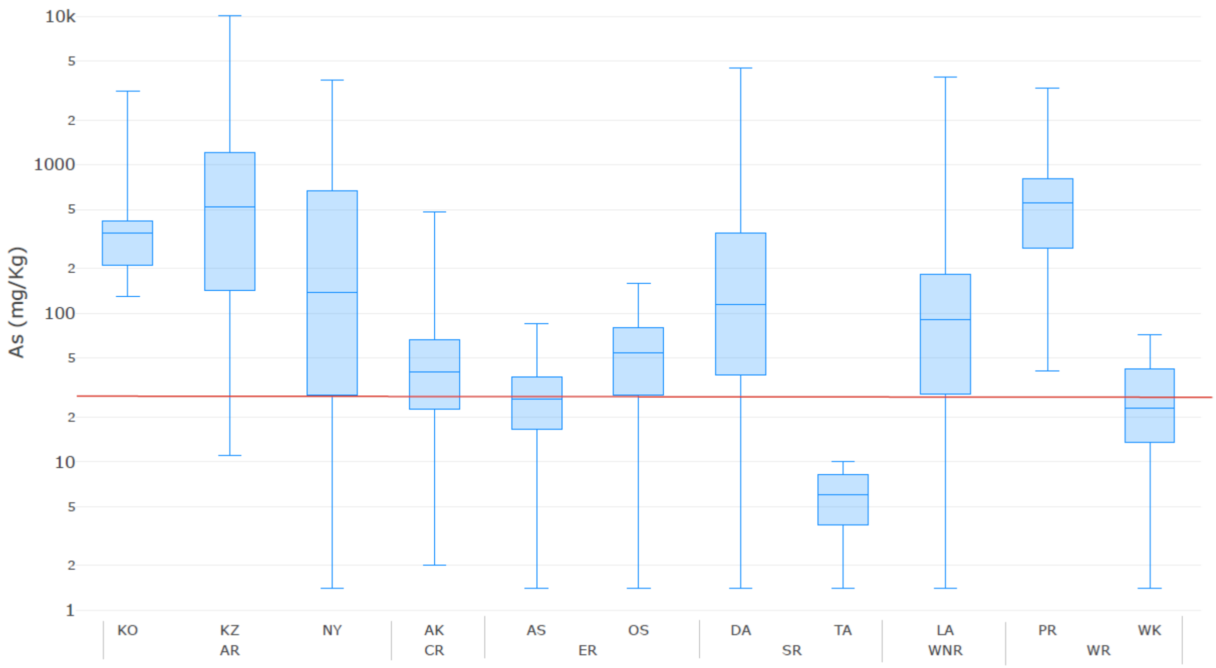


Figure 5.4: Hg, Pb, and As Concentrations in Soil Samples

y axis in mg/kg, log scale
red line = reference values of 200 ppm for lead (Residential Soil; US EPA, 2024a), 10 ppm for mercury, and 25 ppm for arsenic (German Review values for the soil-human pathway for children's play areas).

As can be seen in the graphs above, the distribution of the data for mercury and arsenic show that the majority of the soil samples are above the reference values. This is the opposite for lead, where the distribution is well below the reference value. It is striking that the arsenic concentrations reported above the reference value are very high, reaching a maximum value of 1,066 mg/kg (42 times the reference value). Below is the geographic distribution of the soil samples taken from the Konongo Zongo site with their respective concentrations.

Figure 5.5: Mercury and Arsenic Concentrations (µg/m³) in Soil at Konongo Zongo

5.3 Water

A total of 69 water samples were analyzed by ICP-MS to determine the concentrations of arsenic, lead, cadmium, and mercury across all sites. The reference values used to compare the data correspond to current Ghanaian regulations, which are 0.001 mg/L for mercury, 0.01 mg/L for lead, 0.003 mg/L for cadmium, and 0.01 mg/L for arsenic.

The analysis revealed mercury levels in excess of the permissible limits in multiple water samples. The concentrations of mercury in these samples surpassed the national threshold of 0.001 mg/L, with a maximum of 0.01 mg/L.

The analysis revealed lead levels that exceeded the permissible limit in several water samples, with concentrations that surpassed the national threshold of 0.01 mg/L. The maximum level was recorded at 0.97 mg/L in Asiakwa, where approximately 50% of the water samples were found to be above the established threshold.

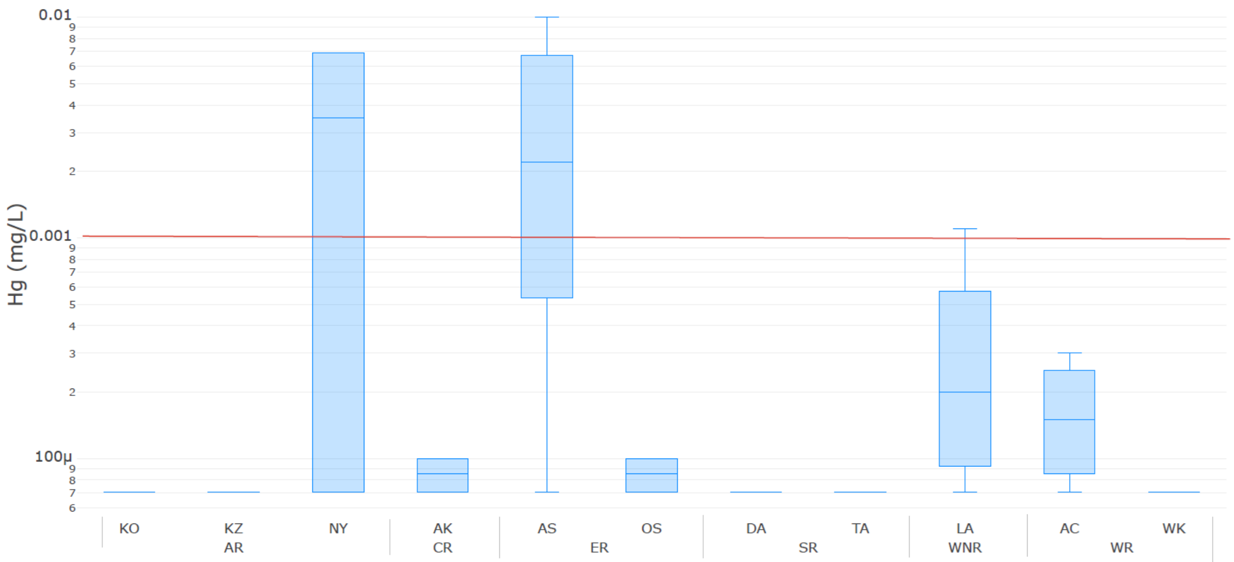
In three sites (Konongo Odumase, Nyamebekyere, Ankobra), total arsenic concentrations exceeded the national threshold of 0.01 mg/L. The maximum level was recorded at 3.30 mg/L in Konongo Odumase.

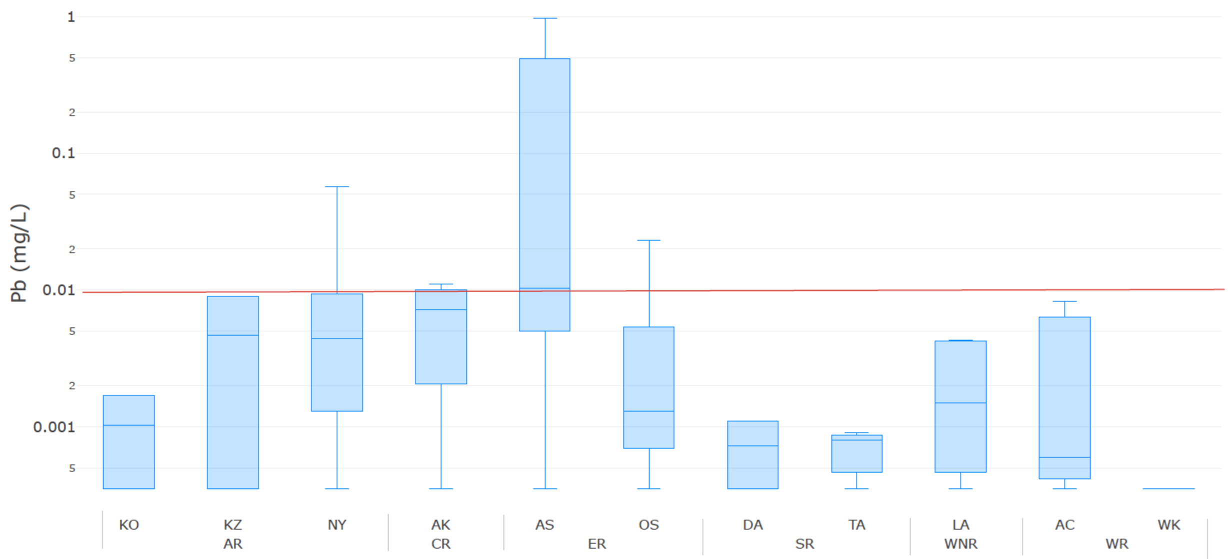
The results are shown in the following table.

Table 5.3 Heavy Metals Concentration in Water Samples (mg/L)

			Hg				**Pb**				**Cd**				**As**			
Region	Site	# Samples	Av	Max	Min	SD	Av	Max	Min	SD	Av	Max	Min	SD	Av	Max	Min	SD
AR	KO	2	<RL	<RL	<RL	<RL	0.0009	0.0017	<RL	0.0012	<RL	<RL	<RL	<RL	1.6519	3.3000	0.0037	2.3308
	KZ	3	<RL	<RL	<RL	<RL	0.0030	0.0090	<RL	0.0052	<RL	<RL	<RL	<RL	0.0033	0.0089	<RL	0.0049
	NY	8	0.0009	0.0069	<RL	0.0024	0.0109	0.0570	<RL	0.0191	<RL	<RL	<RL	<RL	0.0196	0.0830	<RL	0.0297
CR	AK	4	<RL	0.0001	<RL	0.0001	0.0046	0.0110	<RL	0.0055	0.0001	0.0002	<RL	0.0001	0.0003	0.0013	<RL	0.0007
ER	AS	7	0.0021	0.0100	<RL	0.0037	0.1415	0.9700	<RL	0.3654	0.0007	0.0051	<RL	0.0019	0.0032	0.0160	<RL	0.0059
	OS	10	<RL	0.0001	<RL	<RL	0.0037	0.0230	<RL	0.0071	<RL	<RL	<RL	<RL	0.0029	0.0190	<RL	0.0058
SR	DA	10	<RL	<RL	<RL	<RL	0.0001	0.0011	<RL	0.0003	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
	TA	5	<RL	<RL	<RL	<RL	0.0003	0.0009	<RL	0.0005	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
WNR	LA	11	0.0002	0.0011	<RL	0.0003	0.0010	0.0043	<RL	0.0017	<RL	<RL	<RL	<RL	0.0034	0.0140	<RL	0.0056
WR	AC	4	0.0002	0.0003	<RL	0.0001	0.0022	0.0083	<RL	0.0041	<RL	0.0001	<RL	0.0001	0.0747	0.1600	0.0077	0.0728
	WK	5	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL

RL = reporting limit, SD = standard deviation, AV = mean, min = minimum, max = maximum
red = above reference values per Ghanaian regulations of 0.001 mg/L for mercury, 0.01 mg/L for lead, 0.003 mg/L for cadmium, and 0.01 mg/L for arsenic


Hg (mg/L)
0.01
0.001
100μ
KO
KZ
NY
AK
AS
OS
DA
TA
LA
AC
WK
AR
CR
ER
SR
WNR
WR


Pb (mg/L)
1
0.1
0.01
0.001
KO
KZ
NY
AK
AS
OS
DA
TA
LA
AC
WK
AR
CR
ER
SR
WNR
WR

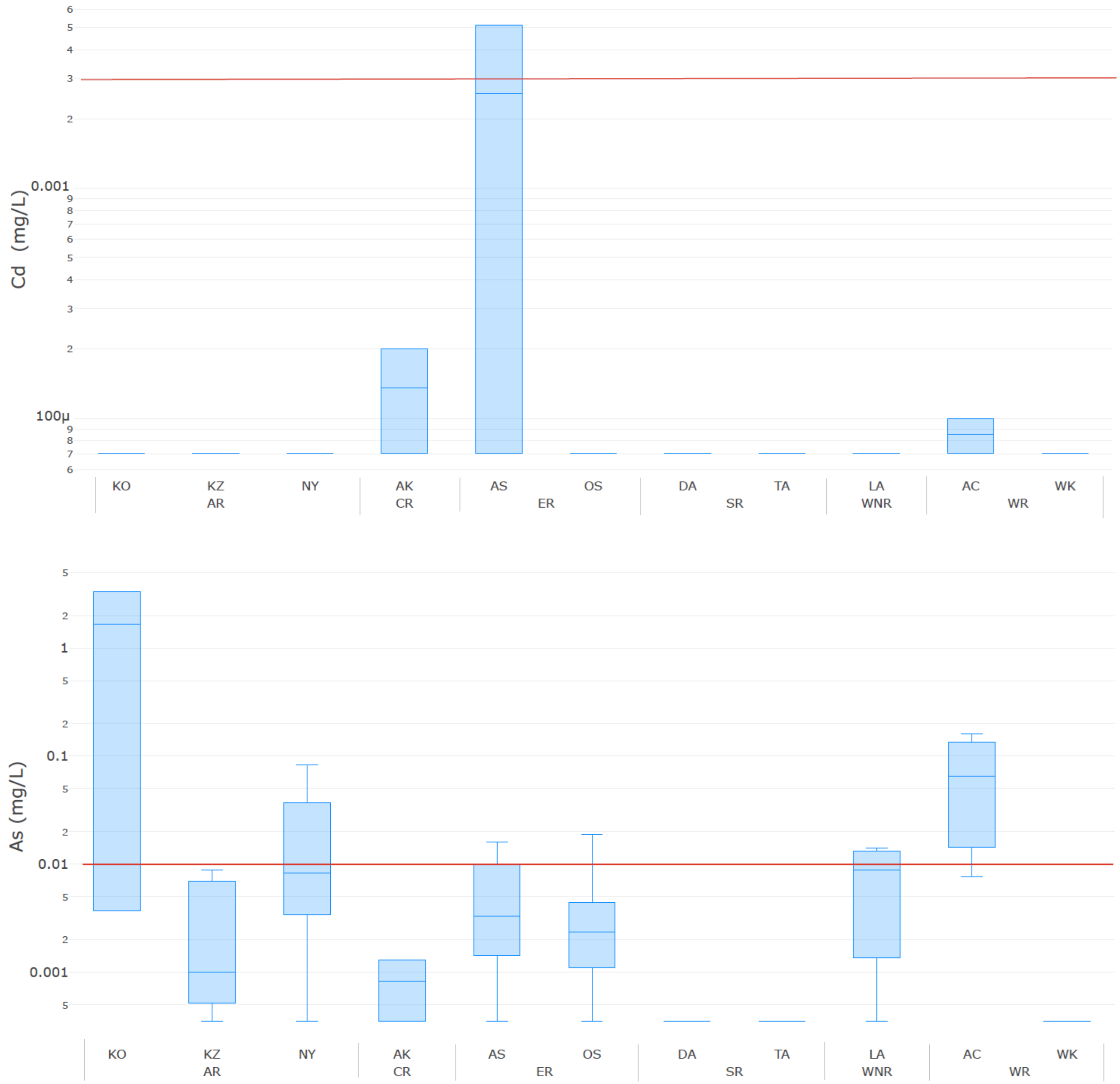


Figure 5.6: Heavy Metals Concentration in Water Samples

Box plots, y axis in mg/L, log scale.
red line = reference values per Ghanaian regulation of 0.001 mg/L for mercury, 0.01 mg/L for lead, 0.003 mg/L for cadmium, and 0.01 mg/L for arsenic.

Considering the distribution of water sample data, we can observe that the Asiakwa (AS) site in the Eastern Region presents a significant percentage of water samples that exceed the reference value for mercury and lead and is also the only site that reports cadmium concentrations in water above the reference value. Nyamebekyere (NY) site in the Central Region also reports important numbers of samples above the reference value for mercury and arsenic. However, the most critical value corresponds to the Konongo Odumase (KO) site in the Ashanti Region, where the maximum arsenic value (1.65 mg/L) exceeds the reference value by 160 times.

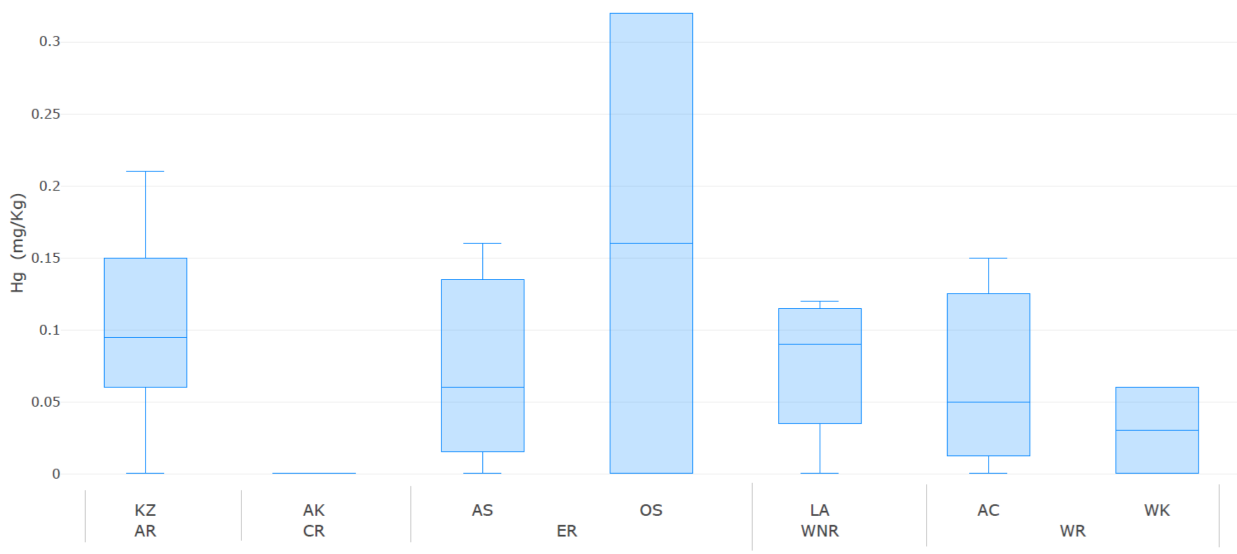
5.4 Fish

Considering that heavy metals have significant bioaccumulation effects on fish, the results for heavy metals in fish are detailed separately from other foods sampled. Since Ghana does not have permissible limits for heavy metals for fish, the "maximum levels for contaminants in food" used here for mercury and cadmium are those of the European Union (EU 2023/915; European Commission, 2023; European Commission, 2025). For lead, WHO/FAO standards were applied (FAO & WHO, 1995) and for arsenic, Chinese Standards were applied (USDA, 2018). The maximum levels are 0.5 mg/kg for total mercury, 0.3 mg/kg for lead, 0.05 mg/kg for cadmium, and 0.1 mg/kg for arsenic. The results are shown in Table 5.4.

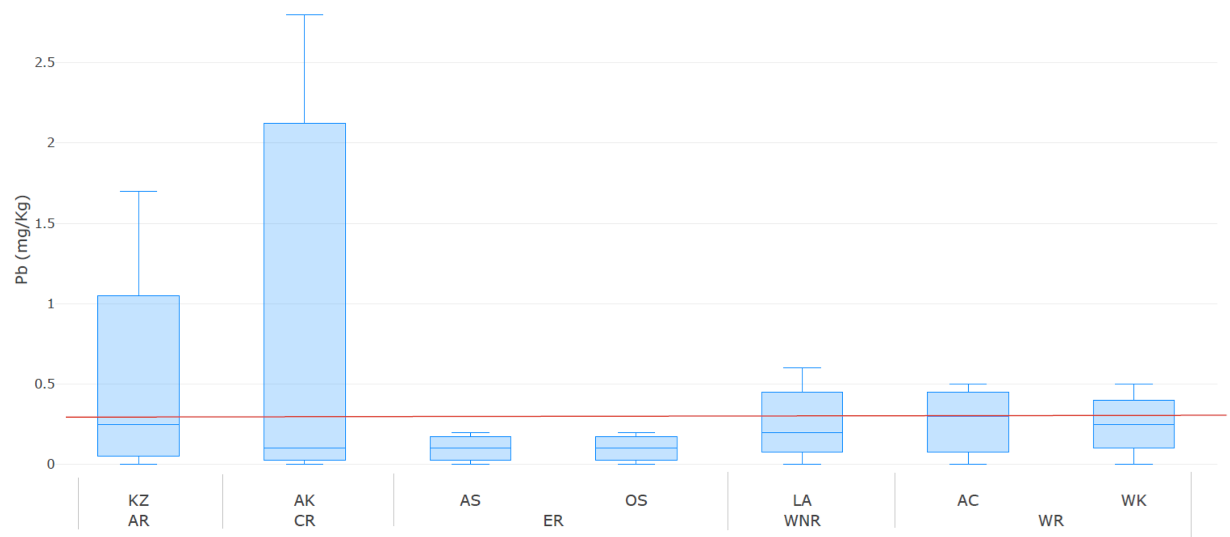
Table 5.4: Heavy Metals Concentration in Fish Samples (mg/kg)

Region	Site	# Samples	Hg				Pb				Cd				As			
			Av	Max	Min	SD	Av	Max	Min	SD	Av	Max	Min	SD	Av	Max	Min	SD
AR	KZ	7	0.087	0.21	<RL	0.078	0.314	1.70	<RL	0.628	0.081	0.20	<RL	0.069	0.636	3.09	<RL	1.100
CR	AK	7	<RL	<RL	<RL	<RL	0.457	2.80	<RL	1.034	0.390	2.73	<RL	1.032	0.444	2.82	<RL	1.050
ER	AS	4	0.070	0.16	<RL	0.066	0.100	0.20	<RL	0.082	<RL	<RL	<RL	<RL	0.120	0.24	<RL	0.101
	OS	7	0.046	0.32	<RL	0.121	0.057	0.20	<RL	0.079	<RL	<RL	<RL	<RL	0.049	0.20	<RL	0.085
WNR	LA	7	0.043	0.12	<RL	0.056	0.200	0.60	<RL	0.224	0.073	0.11	<RL	0.050	0.731	1.14	0.12	0.362
WR	AC	7	0.029	0.15	<RL	0.057	0.114	0.50	<RL	0.204	0.090	0.11	<RL	0.040	0.874	1.58	0.41	0.413
	WK	7	0.009	0.06	<RL	0.023	0.171	0.50	<RL	0.189	0.100	0.12	0.08	0.013	0.199	0.60	<RL	0.252

RL = reporting limit, SD = standard deviation, AV = mean, min = minimum, max = maximum
red = above maximum levels: 0.5 mg/kg for mercury (European Commission, 2023), 0.3 mg/kg for lead (FAO & WHO, 1995), 0.05 mg/kg for cadmium (European Commission, 2023), and 0.1 mg/kg for arsenic (USDA, 2018).



Hg (mg/Kg)
0.3
0.25
0.2
0.15
0.1
0.05
0
KZ
AR
AK
CR
AS
OS
ER
LA
WNR
AC
WK
WR



Pb (mg/Kg)
2.5
2
1.5
1
0.5
0
KZ
AR
AK
CR
AS
OS
ER
LA
WNR
AC
WK
WR

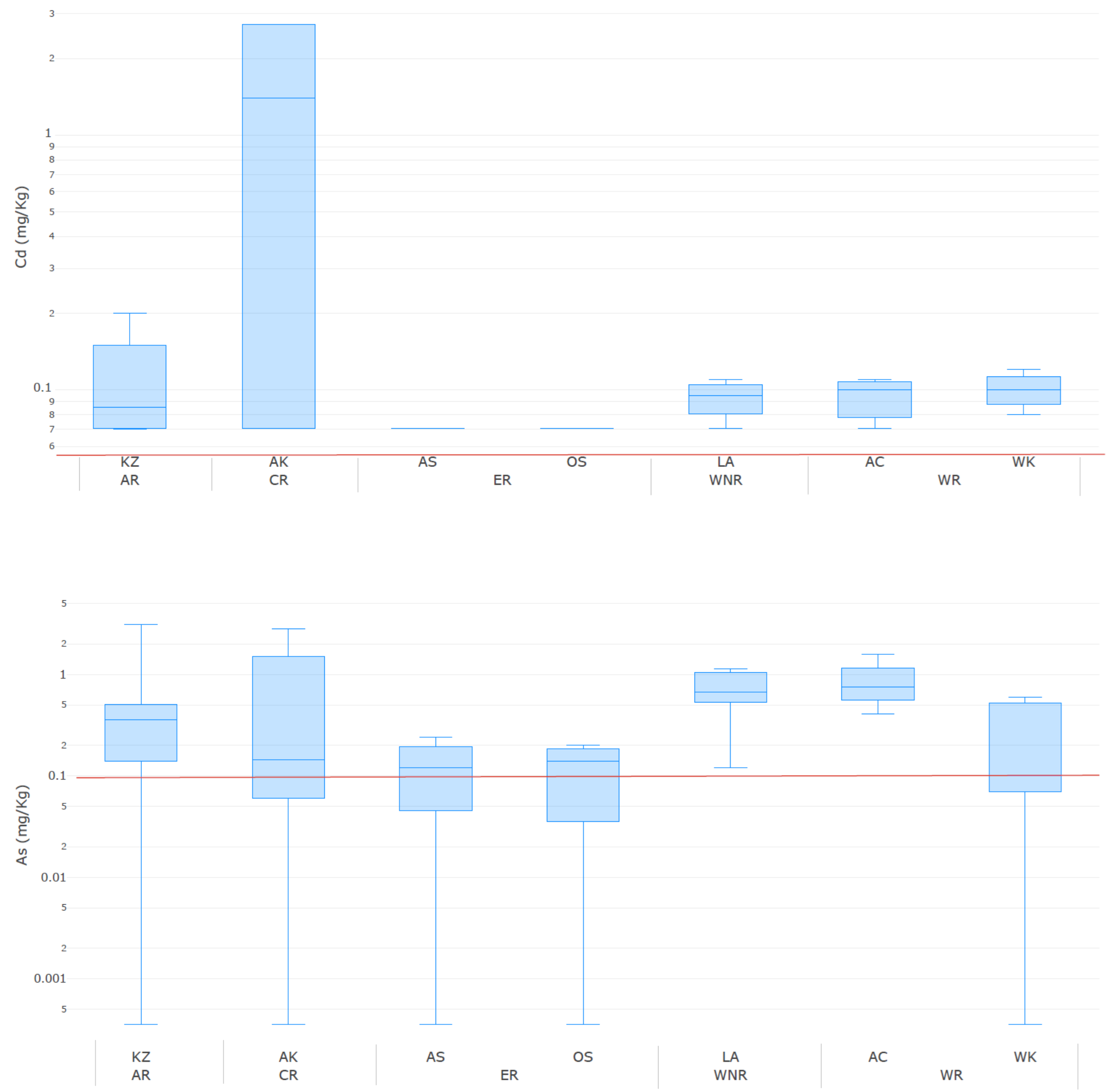


Figure 5.7: Heavy Metals Concentrations in Fish Samples

Box plots, y axis in mg/kg, log scale.
red line = maximum levels: 0.5 mg/kg for total; mercury (European Commission, 2023), 0.3 mg/kg for lead (European Commission, 2023), 0.05 mg/kg for cadmium (FAO & WHO, 1995), and 0.1 mg/kg for arsenic (USDA, 2018).

Mercury concentrations above maximum permissible levels were not found in any of the fish samples taken.

In two sites (Konongo Zongo, Akwaboso), the mean level of lead in fish was above the maximum permissible levels of 0.3 mg/kg. The maximum level of lead detected in the Akwaboso samples was 2.80 mg/kg.

In most of the sites examined, the mean arsenic level in fish samples was found to be above the maximum permissible levels of 0.1 mg/kg. The maximum level was ascertained to be 3.09 mg/kg in the Konongo Zongo site in the Ashanti Region.

The mean cadmium level in fish samples was in most cases found to be above the maximum permissible levels of 0.05 mg/kg. The maximum level was ascertained to be 2.73 mg/kg in the Akwaboso (AK) site in the Central Region (CR).

The data distribution shows a significant number of samples exceeding the reference value for lead, cadmium, and arsenic at the Akwaboso (AK) site in the Central Region (CR). Although arsenic is reported to have values above the maximum permissible levels in almost all sites, it is important to highlight the higher concentrations in Lake Amponsah (LA) site in the Western North and Ankobra Community (AC) in the Western Region.

5.5 Food Crops

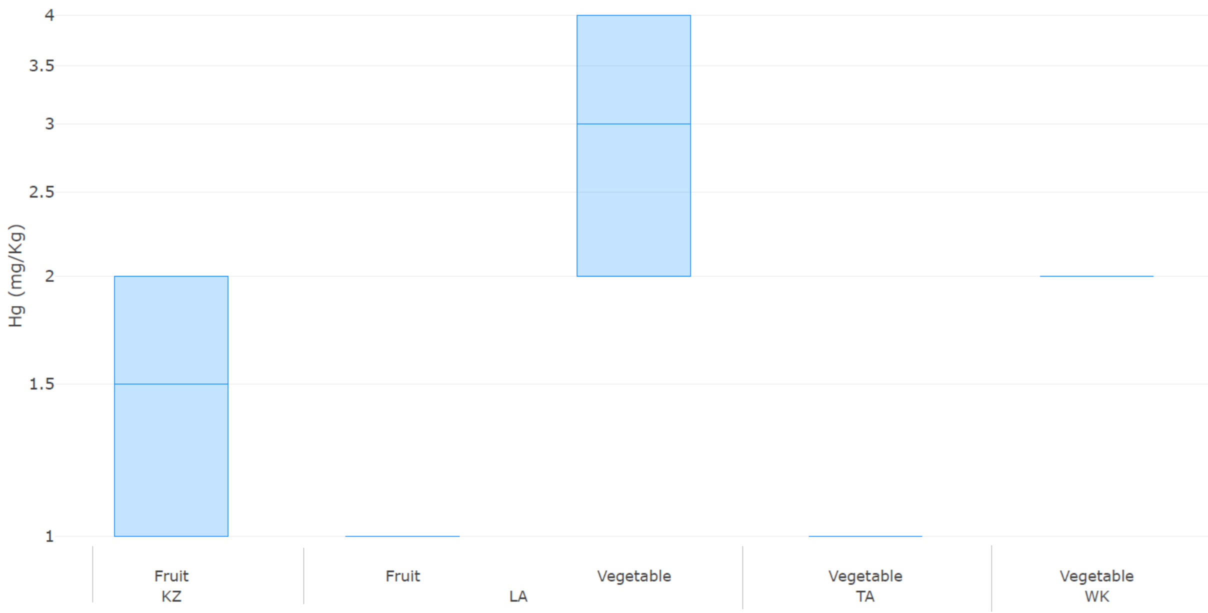
Food crops from the study area were initially categorized based on their general botanical characteristics as follows:

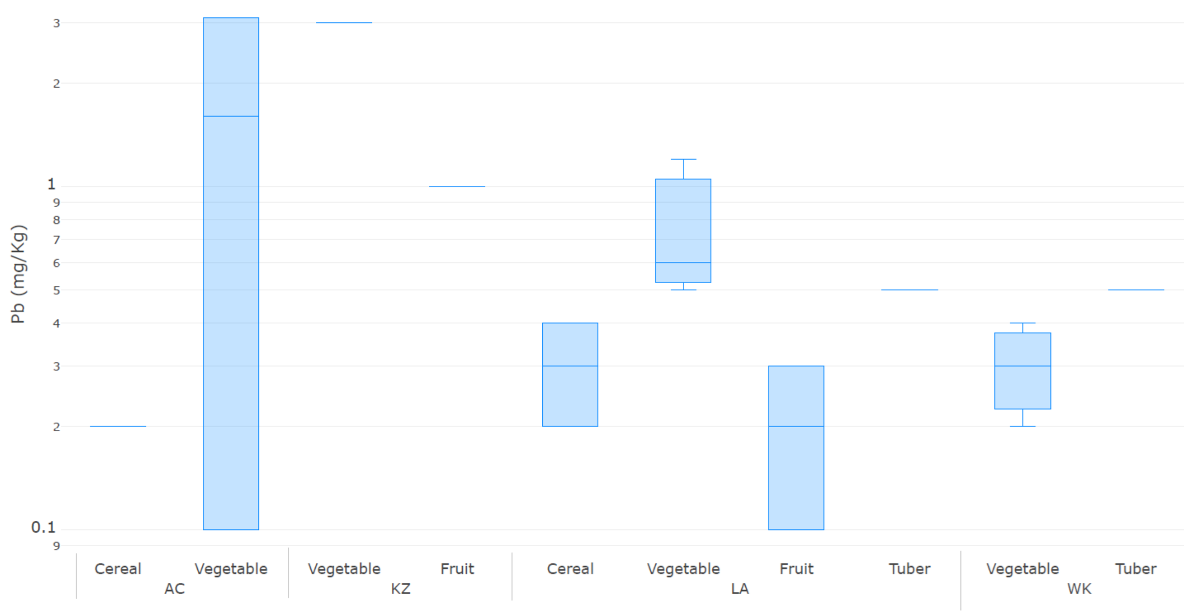
- Cereals (grains): Maize, rice, millet, etc.
- Legumes: Beans, groundnuts, etc.
- Root and Tuber Crops: Cassava, potatoes, yams
- Vegetables: Tomatoes, carrots, onions, spinach, cabbage, lettuce
- Fruits: Mangoes, oranges, bananas, pineapples, plantains

In Ghana, specific national standards for heavy metals in food are not clearly defined in available sources. However, the limits established by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) are often used as reference points in studies conducted in the country. A more detailed analysis with additional information is required to determine the true impact of the data obtained.

To compare the results from this study, which are given in mg contaminant per kg food, one available option is to use the "maximum levels for contaminants in food" from the WHO/FAO as well as from the European Union (WHO & FAO, 1995; European Commission, 2023) and Chinese Standards for "maximum levels of contaminants in food" (USDA, 2018). For more details, see Table 3.3.

An overview of the results from the laboratory analyses taking the total samples for each of the categories is shown in Appendix A.


Hg (mg/Kg)
4
3.5
3
2.5
2
1.5
1
Fruit
KZ
Fruit
Vegetable
LA
Vegetable
TA
Vegetable
WK


Pb (mg/Kg)
3
2
1
9
8
7
6
5
4
3
2
0.1
9
Cereal
Vegetable
AC
Vegetable
Fruit
KZ
Cereal
Vegetable
Fruit
Tuber
LA
Vegetable
Tuber
WK

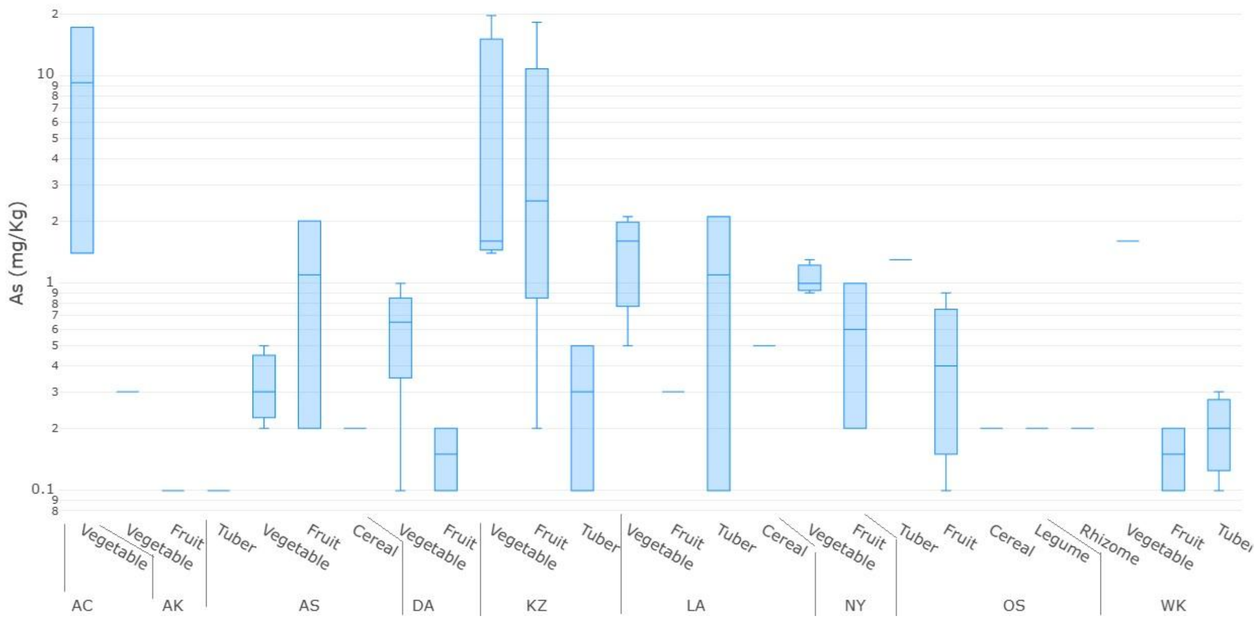


Figure 5.8: Heavy Metals Levels in Food Crops from All Sites

Box plots, y axis in mg/kg, log scale.

A preliminary analysis of the data, taking into account selected categories, reveals concentrations of cadmium only in Western Region in the tuber and fruit categories. On the other hand, arsenic reported significant concentrations in almost all selected categories and sampled regions. The highest reported arsenic values are 19.6 mg/kg in vegetables from the Ashanti Region.

Mercury concentrations were reported in the fruit and vegetable categories (highest value of 4 mg/kg) in three of the regions. The highest average lead concentration, 1.6 ppm, was recorded in vegetables from Ankobra in the Western Region.

A quick visualization of the presence of mercury, lead, and arsenic in each of the categories and regions is shown in the following table.

Table 5.5: Visualization of Heavy Metals Concentrations Found in Food Samples

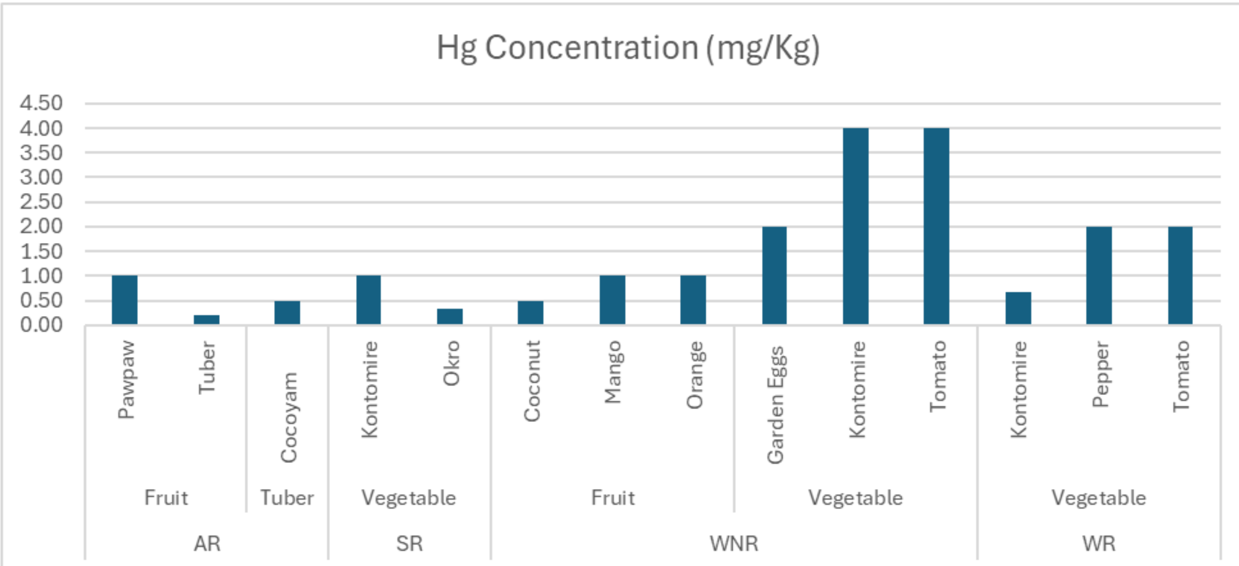
Region	Site	Food	Hg	Pb	Cd	As
AR	KZ	Fruit				
		Tuber				
		Vegetable				
	NY	Fruit				
		Tuber				
		Vegetable				
CR	AK	Fruit				
		Tuber				
		Vegetable				
ER	AS	Cereal				
		Fruit				
		Vegetable				
	OS	Cereal				
		Fruit				
		Legume				
		Rhizome				
SR	DA	Fruit				
		Vegetable				
	TA	Vegetable				
WNR	LA	Cereal				
		Fruit				
		Tuber				
		Vegetable				
WR	AC	Vegetable				
		WK				
	WK	Fruit				
		Tuber				
		Vegetable				

Mercury results obtained for each of the types of food are shown in the following table and graph.

Table 5.6 Mercury Concentration in Food Samples (mg/kg)

Region	Category	Type Food	# Samples	Av	Max	Min	SDv
AR	Fruit	Pawpaw	2	1.00	2	<RL	1.41
		Tuber	5	0.20	1	<RL	0.45
	Tuber	Cocoyam	2	0.50	1	<RL	0.71
SR	Vegetable	Kontomire	1	1.00	1	1	-
		Okro	3	0.33	1	<RL	0.58
WNR	Fruit	Coconut	2	0.50	1	<RL	0.71
		Mango	1	1.00	1	1	-
		Orange	1	1.00	1	1	-
	Vegetable	Garden Eggs	1	2.00	2	2	-
		Kontomire	1	4.00	4	4	-
		Tomato	1	4.00	4	4	-
WR	Vegetable	Kontomire	3	0.67	2	<RL	1.15
		Pepper	1	2.00	2	2	-

		Tomato	1	2.00	2	2	-



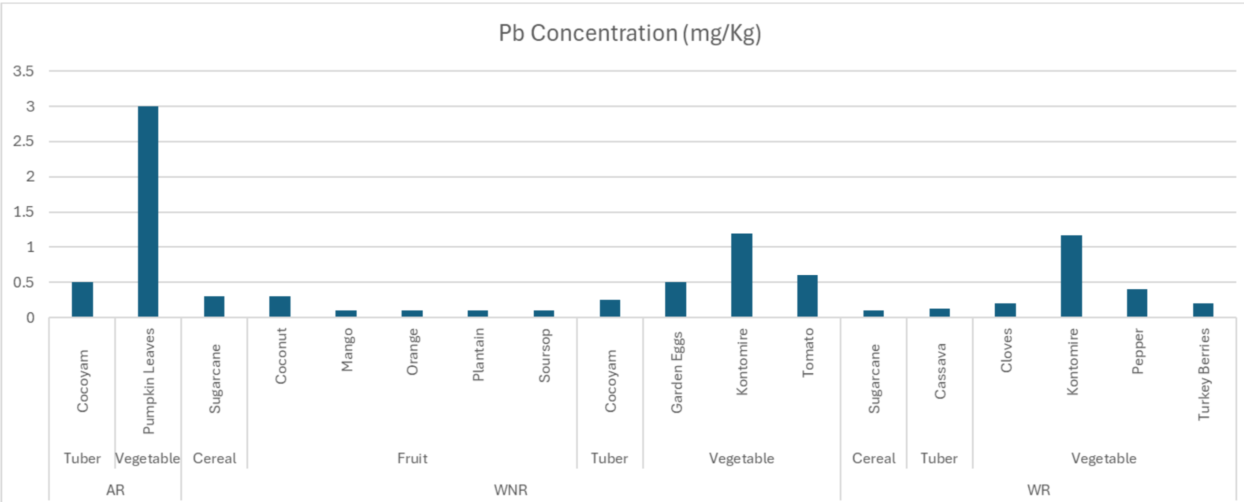
Kontomire and tomato samples in the Western Region showed the highest mercury concentrations at close to 4.0 mg/kg. Elevated mercury concentrations were found in kontomire from three regions and tomato from two regions. The elevated mercury content in kontomire and tomato plants suggests possible bioaccumulation from contaminated soil or irrigation water, potentially linked to mining activities or poor waste management.

Lead results obtained for each type of food are shown in the following table and graph.

Table 5.7: Lead Concentration in Food Samples (mg/kg)

Region	Category	Type Food	# Samples	Av	Max	Min	SDv
AR	Tuber	Cocoyam	2	0.5	1	<RL	0.71
	Vegetable	Pumpkin Leaves	1	3	3	3	-
WNR	Cereal	Sugarcane	2	0.3	0.4	0.2	0.14
	Fruit	Coconut	2	0.3	0.3	0.3	0.00
		Mango	1	0.1	0.1	0.1	-
		Orange	1	0.1	0.1	0.1	-
		Plantain	1	0.1	0.1	0.1	-
		Soursop	1	0.1	0.1	0.1	-
	Tuber	Cocoyam	2	0.3	0.5	<RL	0.35
	Vegetable	Garden Eggs	1	0.5	0.5	0.5	-
		Kontomire	1	1.2	1.2	1.2	-
		Tomato	1	0.6	0.6	0.6	-
WR	Cereal	Sugarcane	2	0.1	0.2	<RL	0.14
	Tuber	Cassava	4	0.1	0.5	<RL	0.25
	Vegetable	Cloves	1	0.2	0.2	0.2	-

		Kontomire	3	1.2	3.1	0.1	1.68
		Pepper	1	0.4	0.4	0.4	-
		Turkey Berries	1	0.2	0.2	0.2	-



A sample of pumpkin leaves from the Ashanti Region showed the highest lead concentration, exceeding 3.0 mg/kg. Kontomire in Western North and Western Regions also displayed high concentrations of around 1.5–1.7 mg/kg.

Consistently elevated Pb levels were found in kontomire, tomato, and garden eggs, indicating potential contamination of agricultural soils or irrigation water in mining areas selected. The same regions saw elevated mercury concentrations for kontomire and tomatoes.

Few samples reported the presence of cadmium. Only three samples in the Western Region had cadmium concentrations, which is not representative of the total number of samples taken. The results are shown in the following table.

Table 5.8: Cadmium Concentration in Food Samples (mg/kg)

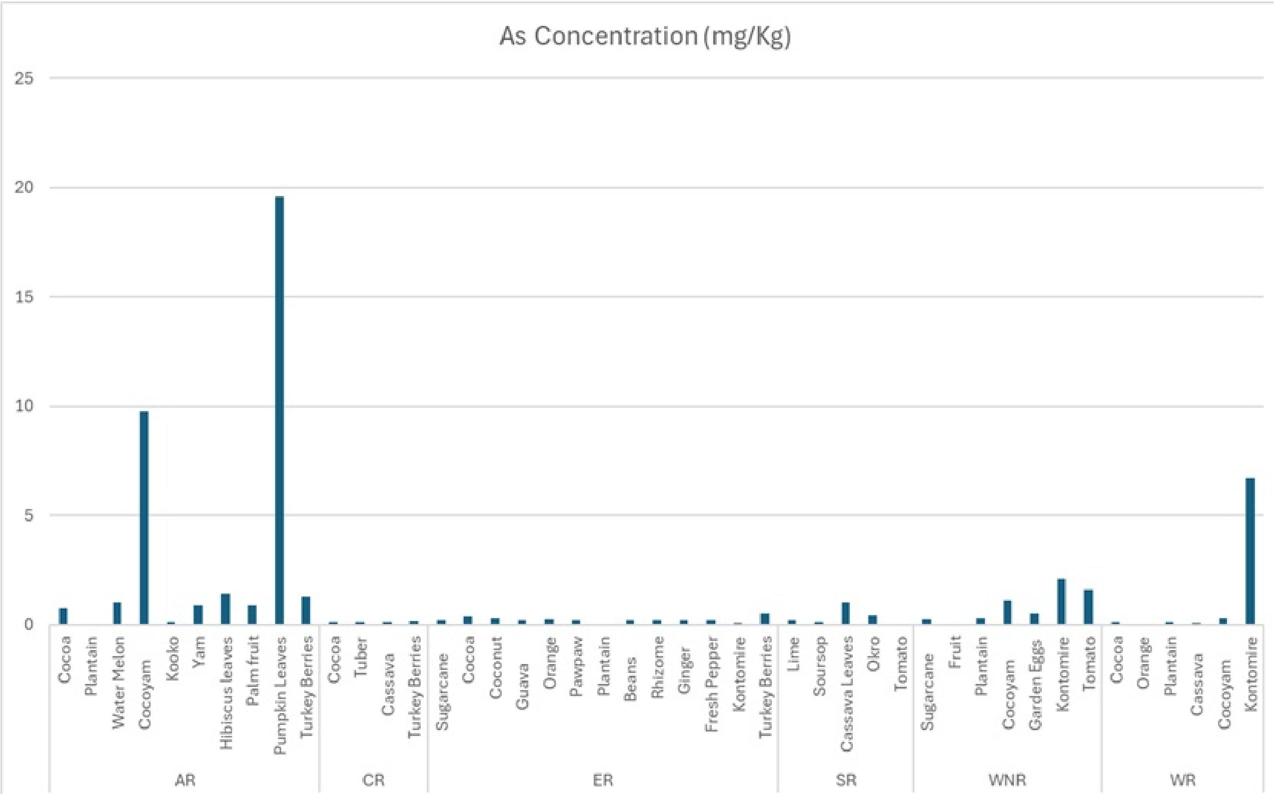
Region	Category	Type Food	# Samples	Av	Max	Min	SDv
WR	Fruit	Cocoa	2	0.2	0.4	<RL	0.2828
	Tuber	Cocoyam	1	1.2	1.2	1.2	-

Arsenic results for each type of food are shown in the following table and graph.

Table 5.9: Arsenic Concentration in Food Samples (mg/kg)

Region	Category	Type Food	# Samples	Av	Max	Min	SDv
AR	Fuit	Cocoa	7	0.7	3.5	<RL	1.33
		Plantain	6	0	0.2	<RL	0.08
		Watermelon	1	1	1	1	-
	Tuber	Cocoyam	2	9.8	18	1.3	11.95

		Kooko	1	0.1	0.1	0.1	-
		Yam	2	0.9	1.3	0.5	0.57
	Vegetable	Hibiscus leaves	1	1.4	1.4	1.4	-
		Palm fruit	1	0.9	0.9	0.9	-
		Pumpkin Leaves	1	20	20	20	-
		Turkey berries	2	1.3	1.6	1	0.42
CR	Fruit	Cocoa	1	0.1	0.1	0.1	-
		Tuber	1	0.1	0.1	0.1	-
	Tuber	Cassava	1	0.1	0.1	0.1	-
	Vegetable	Turkey berries	2	0.2	0.3	<RL	0.21
ER	Cereal	Sugarcane	2	0.2	0.2	0.2	-
	Fruit	Cocoa	6	0.4	2	<RL	0.80
		Coconut	3	0.3	0.9	<RL	0.52
		Guava	1	0.2	0.2	0.2	-
		Orange	3	0.3	0.6	<RL	0.31
		Pawpaw	1	0.2	0.2	0.2	-
		Plantain	5	0	0.1	<RL	0.05
	Legume	Beans	1	0.2	0.2	0.2	-
		Rhizome	1	0.2	0.2	0.2	-
	Rhizone	Ginger	1	0.2	0.2	0.2	-
	Vegetable	Fresh pepper	1	0.2	0.2	0.2	-
		Kontomire	4	0.1	0.3	<RL	0.15
		Turkey berries	1	0.5	0.5	0.5	-
SR	Fruit	Lime	1	0.2	0.2	0.2	-
		Soursop	1	0.1	0.1	0.1	-
	Vegetable	Cassava leaves	1	1	1	1	-
		Okro	3	0.4	0.7	<RL	0.38
		Tomato	2	0.1	0.1	<RL	0.07
WNR	Cereal	Sugarcane	2	0.3	0.5	<RL	0.35
		Fruit	6	0.1	0.3	<RL	0.12
	Fruit	Plantain	1	0.3	0.3	0.3	-
	Tuber	Cocoyam	2	1.1	2.1	0.1	1.41
	Vegetable	Garden eggs	1	0.5	0.5	0.5	-
		Kontomire	1	2.1	2.1	2.1	-
		Tomato	1	1.6	1.6	1.6	-
WR	Fruit	Cocoa	2	0.1	0.1	0.1	-
		Orange	2	0.1	0.1	<RL	0.07
		Plantain	2	0.1	0.2	<RL	0.14
	Tuber	Cassava	4	0.1	0.2	<RL	0.10
		Cocoyam	1	0.3	0.3	0.3	-
	Vegetable	Kontomire	3	6.7	17	1.4	9.06



One sample of pumpkin leaves in Ashanti Region showed the highest As concentration at close to 20 mg/kg. Cocoyam in Ashanti Region and kontomire in the Western Region also displayed notably high arsenic concentrations at around 7–9 mg/kg.

Most food items across the Eastern Region (ER) and Central Region (CR), such as cocoa, guava, plantain, orange, sugarcane, coconut, and beans, showed arsenic concentrations below 1 mg/kg. These levels may be considered within natural background or tolerable daily intake thresholds, depending on form (organic vs. inorganic arsenic).

5.6 Socio-Demographic Survey Summary

The socio-demographic survey was conducted with a total of 79 participants, of which 50.6% were males and 49.4% females from five administrative regions of Ghana: Western Region (41.8%), Ashanti Region (22.8%), Eastern Region (12.7%), Savannah Region (11.4%), and Central Region (11.4%). The purpose of the survey was to gather insights into household composition, educational levels, occupations, housing types, and food access patterns, as part of a broader environmental assessment. Within these regions, respondents were drawn from eight districts, with the largest representation from Tarkwa Nsuaem (22.8%), Obuasi Municipal (12.7%), Bole Bamboi District (12.7%), Fanteakwa South (11.4%), and Upper Denkyira West (11.4%). The remaining districts were Asante Akim Central (10.1%), Prestea Huni-Valley (10.1%), and Bibiani Awiaso Bekwai Municipal (8.9%).

At the community level, Kanyanko accounted for the highest proportion of respondents (22.8%), followed by Nyamebekyere and Tinga (each 12.7%), Osino (11.4%), and Akwaboso (10.1%).

Other communities included Bibiani Old Town (7.6%), Prestea (7.6%), Konongo Zongo (8.9%), and several smaller settlements. Notably, the vast majority of participants (89.9%) resided in rural areas, with only 10.1% from urban settings.

In terms of education, 39.2% of respondents had completed primary education ranging from Class 6 to Junior High School (JHS 3) while 31.7% had attained senior high school or technical and vocational education and training (TVET) qualifications. Only 1.3% had achieved undergraduate and graduate/postgraduate education with 4.0% having other forms of educational experience. 22.8% of the participants were illiterate. The distribution reflects participants with foundational basic education but limited access to tertiary education opportunities.

Regarding occupational status, 31.2% were miners, 21.5% were traders, 17.2% were farmers, and 12.9% were self-employed. 6.4% of the respondents were skilled workers while students accounted for 2.2%, and 1.1% were unemployed. The remaining 7.5% were engaged in other unspecified occupations. This indicates that the community members primarily rely on natural resource-based occupations, particularly mining and farming, with some degree of occupational diversity.

With housing, 27.9% of respondents lived in self-contained units, 21.5% in single rooms, 13.9% in huts, and another 13.9% in apartments. Wooden structures housed 7.6% of the respondents, 6.3% lived in duplexes, and 8.9% in other housing types.

Of those surveyed, 62.0% of the respondents owned their homes, 34.2% lived in rented properties, and 3.8% were caretakers of other people’s houses. These numbers point to stable and established community with comparatively high rates of home ownership.

Most of respondents (79.8%) sourced their food from the market, while 19.2% relied on homegrown produce. 20.3% of respondents reported always purchasing food, 34.2% did so once a week, 15.2% rarely bought food, and 2.5% never bought food. This pattern shows a strong dependence of respondents on market systems for food.

In conclusion, the socio-demographic profile of the surveyed communities surveyed shows a population with strong ties to traditional livelihoods, especially mining and farming, and with modest levels of educational attainment. The reliance on food from the market highlights the need for sustainable food security measures, while prevalence of home ownership indicates community rootedness.

Chapter 6 DISCUSSION

6.1 Summary of Results

This study assessed mercury levels in ambient air and measured the concentrations of mercury, arsenic, cadmium, and lead in soil, water, fish, and food crops across several sites in Ghana, with a focus on areas impacted by artisanal and small-scale gold mining (ASGM).

6.1.1 Mercury in Air

Ambient air sampling showed that most sites recorded mercury concentrations below the Ghanaian maximum permissible level of 1 µg/m³ (GSA, 2024). However, samples from Wassa Kayianko exceeded this limit, reporting a mean value of 1.84 µg/m³ and peak measurements up to 150.2 µg/m³. These high levels were likely linked to smelting of amalgam activities and possibly higher daytime temperatures which increase mercury volatilization.

6.1.2 Soil Contamination

Among 1,040 soil samples, cadmium was not detected above the reporting limit. Mercury levels exceeded the reference value of 10 ppm at three sites, with Konongo Zongo reporting the highest mean (56 ppm). Some previous studies have reported higher levels of mercury in soils from ASGM areas, with concentrations exceeding 10 ppm in some locations (Bempah & Ewusi, 2016). Arsenic levels were markedly high across many sites, far exceeding the reference value of 25 ppm. Konongo Zongo again showed extreme arsenic contamination, with a mean of 1,066 ppm and a maximum of 10,060 ppm. In contrast, average lead levels were below the 200 ppm EPA guideline; however, individual hotspots like Dakrupe showed values as high as 3,899 ppm.

6.1.3 Water Contamination

Among 69 water samples, several exceeded Ghanaian standards: 0.001 mg/L for mercury, 0.01 mg/L for lead and arsenic, and 0.003 mg/L for cadmium. Mercury levels reached up to 0.01 mg/L in some areas, particularly at Asiakwa. Lead levels were especially elevated in Asiakwa, with a maximum of 0.97 mg/L. Arsenic peaked at 3.3 mg/L in Konongo Odumase. Cadmium exceeded the limit only at Asiakwa.

6.1.4 Contamination in Fish

Fish samples revealed widespread contamination. Although mercury levels remained below the EU threshold of 0.5 mg/kg, lead exceeded the 0.3 mg/kg WHO/FAO limit at Akwaboso and Konongo Zongo (max: 2.80 mg/kg). Arsenic levels were above the permissible limit of 0.1 mg/kg at most sites, peaking at 3.09 mg/kg in Konongo Zongo. Cadmium levels were also high, with a maximum of 2.73 mg/kg at Akwaboso, far above the 0.05 mg/kg EU limit.

6.1.5 Contamination in Food Crops

Western Region and Ashanti Region consistently show the highest concentrations of all heavy metals across multiple food types. Leafy vegetables such as kontomire and pumpkin leaves are repeatedly found to have the highest concentrations of all three metals, indicating a strong tendency for potential bioaccumulation in plant foliage.

6.2 Comparison with Other Studies and Implications

6.2.1 Mercury Contamination in Air

In this Heavy Metals Impact Assessment, mercury values were high especially in the Ashanti Region and particularly in soil and water, potentially impacting the aquatic food chain in these sectors through potential methylation in the aquatic system, affecting predatory fish in these areas or downstream. Ambient air sampling showed that most sites recorded mercury concentrations below the Ghanaian maximum permissible level of 1 µg/m³ (GSA, 2024). However, samples from Wassa Kayianko exceeded this limit, reporting a mean value of 1.84 µg/m³ and peak measurements up to 150.20 µg/m³. These high levels were likely linked to smelting of amalgam activities as confirmed by Al-Hassan et al. (2019) and possibly higher daytime temperatures which increase mercury volatilization. According to Gyamfi et al. (2020), both miners and non-miners within a mining community are at risk of adverse health effects due to the inhalation of mercury vapor as Hg can evaporate from mining sites and be transported by wind to nearby communities (Mantey et al., 2020). Our finding of elevated mercury air levels at Wassa Kayianko is consistent with Bempah et al. (2016), who recorded ambient Hg levels exceeding 100 µg/m³ in Tarkwa mining sites. These results are corroborated by UNEP (2019), which highlights that open amalgam burning in ASGM regions can cause local spikes well above 50 µg/m³.

6.2.2 Soil Contamination

Among 1,040 soil samples, cadmium was not detected above the reporting limit. Mercury levels exceeded the reference value of 10 ppm at three sites, with Konongo Zongo reporting the highest mean (56 ppm). Some previous studies have reported lower levels of mercury in soils from ASGM areas, with concentrations below 10 ppm in some locations (Bempah & Ewusi, 2016; Akabzaa et al., 2012). However, higher concentrations of mercury (Hg) have been documented elsewhere in Talensi (Ghana), Myanmar, and Kenya, with levels reaching 71.00 77.44 and **100.00 mg/kg**, respectively (Gyamfi et al., 2021; Tun et al., 2020; Rafiei et al., 2010). These high levels are a result of the use of mercury in gold extraction processes at the mining sites (Opoku et al., 2024). Arsenic levels were markedly high across many sites, far exceeding the reference value of 25 ppm. Konongo Zongo again showed extreme arsenic contamination, with a mean of 1,066 ppm and a maximum of 10,060 ppm. Similar arsenic concentrations of 1752ppm (Bempah et al., 2013) and 8305 ppm (Ahmad & Carboo, 2000) have been reported in soils from Obuasi, Ghana. Additionally, a forest reserve recorded arsenic levels as high as 138.63 ppm largely influenced by surrounding artisanal mining activities (Osei et al., 2024). In contrast, average lead levels were below the 200 ppm EPA guideline; however, individual hotspots like Dakrupe showed values as high as 3,899 ppm. These low values are in agreement with those reported in previous studies, such as 0.91-2.48ppm (Wiafe et al, 2022), 0.076 ppm (Awuah & Kyere, 2024), 3.6–63.20 ppm (Darko et al.,2019), 5-71ppm (Kazapoe 2022).

6.2.3 Water Contamination

Among the 69 water samples, several recorded heavy metal concentrations exceeding Ghanaian standards: 0.001 mg/L for mercury, 0.01 mg/L for lead and arsenic, and 0.003 mg/L for cadmium. Mercury levels were high reaching up to 0.01 mg/L particularly at Asiakwa. Mercury concentrations in the Tano and Ankobra basins remained below the standard except River Asuo Kofi values that were above the limit (Asare-Donkor & Adimado, 2016). Comparable levels were also reported by Attiogbe et al. (2020) in Lake Amponsah where Hg concentrations of 0.0053mg/L were attributed to direct discharge from artisanal mining operations.

Lead concentrations were highest in Asiakwa, peaking at 0.97 mg/L, almost 100 times above the recommended limit. This pattern is consistent with findings by Bessah et al. (2021), who observed lead concentrations were above the recommended limit in about 30% of the 25 rivers assessed in the Pra River Basin.

Arsenic levels reached a maximum of 3.3 mg/L in Konongo Odumase, a site known for its high arsenopyrite content (Owusu -Sekyere et al., 2023). Although lower arsenic values were recorded in Lake Amponsah, they still exceeded the limit of 0.01mg/L due to the presence of gold-bearing arsenopyrite rocks in the region (Attiogbe et al., 2020). Arsenic in mined rocks can leach into water bodies. Arsenic is carcinogenic in all its oxidation states and high exposure can cause death (Patel et al., 2023).

Cadmium exceeded the limit only at Asiakwa. A study conducted in the Kibi traditional area recorded high levels of Cadmium and other metals in surface water samples. Mean lead levels ranged from 0.006 to 0.025mg/L, while arsenic levels were as high as 0.18mg/L. Also, mean concentrations of 0.0372 were recorded for Cd (Asamoah, 2012).

Cobbina et al. (2015) found that heavy metal concentrations (mercury, zinc, lead, cadmium, and arsenic) in drinking water sources in Northern Ghana exceeded the recommended limits in the Nangodi and Tinga areas.

6.2.4 Fish Contamination

Fish samples analyzed in this study revealed widespread contamination with heavy metals. Although mercury concentrations remained below the EU threshold of 0.5 mg/kg, consistent with previous findings by Rajaee et al. (2015) in Kejetia and by Asare-Donkor & Adimado 2016 in the Ankobra and Tano River basins, other metals were detected at concerning levels. Lead concentrations exceeded the 0.3 mg/kg WHO/FAO limit at Akwaboso and Konongo Zongo reaching a peak of 2.80 mg/kg. Arsenic levels were also above the permissible limit of 0.1 mg/kg at most sites, peaking at 3.09 mg/kg in Konongo Zongo. Cadmium levels were particularly high at Akwaboso, with a maximum of 2.73 mg/kg, exceeding the EU limit of 0.05mg/kg by more than 50-fold. The elevated levels of lead, arsenic and cadmium in fish raise urgent public health concerns as they are widely consumed as sources of primary protein.

6.2.5 Food Contamination

Heavy metal contamination was also evident in food crops sampled across the regions particularly in the Western Region and Ashanti Region which consistently showed the highest concentrations of all the heavy metals analysed. Leafy vegetables such as *Xanthosoma sagititolium* (kontomire) and *Telfairia occidentalis* (pumpkin) leaves are repeatedly found to have the highest concentrations of arsenic, cadmium and mercury, indicating a strong tendency for potential bioaccumulation in plant foliage. This observation supports findings by Essumang et al. (2007), who reported concentrations of these metals in *Xanthosoma sagititolium* (cocoyam) and *Colocasia esculenta* (water cocoyam) exceeding WHO recommended levels. Further evidence of contamination was found in cassava (*Manihot esculenta*) sourced from Tweapease, Nyamebekyere and Ahansonyewodea, (all mining intensive communities), where mercury levels exceeded permissible limits (Addai-Arhin et al., (2022).

6.2.6 Leaf Vs Fruit Contamination

The observed trend of higher contaminant levels in leafy tissues compared to fruits is consistent with findings from numerous studies on heavy metal accumulation in plants. This phenomenon can be attributed to several factors: firstly, the large surface area of leaves makes them efficient accumulators of airborne contaminants, including particulate matter and gaseous forms of mercury and other metals, originating from sources such as industrial emissions and coal-fired power plants (Li et al., 2017; Zhang et al., 2018). Secondly, while roots absorb contaminants from the soil, the translocation of certain heavy metals, including lead and arsenic, from the leaves and other vegetative parts to the reproductive organs (fruits and grains) can be limited, leading to their preferential accumulation in foliar tissues (Collin et al., 2022; Qin et al., 2021).

6.3 Potential Health Implications

The results of this study indicate widespread contamination by heavy metals particularly arsenic, lead, mercury, and cadmium in soil, water, fish, and food crops across ASGM-impacted communities. These findings raise significant public health concerns. Chronic exposure to arsenic, especially at elevated levels sometimes found in soil, water, and food, is associated with increased health risks.

For lead, young children are particularly susceptible to lead poisoning because they absorb more lead from their environments than adults, and their central nervous systems are still developing. Lead exposure can affect children's brain development, even at low levels (Lanphear, 2019; Amitai, 2010). It can result in reduced intelligence, behavioral changes, and reduced educational attainment and lifetime earnings (Nevin, 2007; Wright, 2008). Pregnant women with high blood lead levels may suffer from adverse birth outcomes. Lead can easily cross the placenta to the fetus (Flora, 2012; Cantor, 2024). There is a robust body of research indicating that lead exposure is associated with a wide range of health consequences, including stunting, anemia, kidney disorders, reproductive toxicity, weakened immune systems, gastrointestinal issues, and an increased risk for cardiovascular diseases (Bellinger, 2008; Bergdahl & Skerfying, 2022). The presence of elevated levels of lead in water and foodstuffs, with concentrations often exceeding the guidelines established by the World Health Organization and the Food and Agriculture Organization, is a matter of particular concern.

Cadmium, found in fish and some water samples above permissible levels, is known to as a health hazard. Depending on the dose and time length of exposure, chronic exposure has been linked to kidney damage, respiratory problems, and osteoporosis (Järup, 2003; Nordberg et al., 2022). Cadmium increases the risk of cardiovascular disease (Akhtar et al., 2021; Rasin & Sreekanth, 2023). It is a human carcinogen in the IARC Group I category that can cause cancer of the lungs and other organs (Nordberg et al., 2022).

The cumulative exposure to this cocktail of toxic metals through multiple pathways, ingestion, inhalation, and dermal contact is a serious health hazard. To evaluate this risk further research is needed. To obtain data, human biomonitoring studies which include the multiple toxic metals and focus on risk groups such as miners, pregnant women and children are needed. There is an urgent need for targeted health interventions, including biomonitoring of exposed populations particularly in the Ashanti and Western regions, public education, and preventive measures to reduce exposure sources.

6.4 Limitations

The assessment of heavy metals in environmental and food matrices provides valuable insight into contamination levels across multiple Ghanaian mining regions. However, several limitations should be acknowledged to contextualize the results and guide further investigations.

Temporal variability was not fully addressed. Measurements such as air mercury concentrations are highly sensitive to the time of day and temperature. Air sampling was limited to specific periods, and peak readings at sites like Wassa Kayianko (up to 150.20 $\mu g/m^3$) could be overestimated due to localized smelting events or high ambient temperatures, limiting generalizability across time.

Spatial heterogeneity affects result interpretation. While over 1,000 soil samples were taken, localized anomalies such as extreme arsenic levels in Konongo Zongo (10,060 ppm) may not reflect regional averages but represents a localized concern. Additionally, sampling density varied between environmental media, with fewer water and food crop samples (e.g., only 69 water samples across all sites), limiting robust spatial analysis.

The speciation of metals was not performed, due to limited technical capacity in Ghana. For mercury and arsenic in food, only total concentrations were measured. Since toxicity is driven by specific species (e.g., methylmercury, inorganic arsenic), risk assessments based on total concentrations may overestimate actual health threats. To assess the health risks from consumption of these food, further analysis, such as speciation of fish and food samples, would be required. Arsenic speciation is defined as the various chemical forms (species) in which arsenic can exist. These forms exhibit different levels of toxicity. The data from this category are limited for use in analysis because only total mercury levels were available from the laboratory, yet only methylmercury can be absorbed. Further research would be needed to assess the risk adequately. This issue is especially relevant for mercury in food and arsenic in fish and food samples.

The number of samples, especially of food, tends not to be representative for decision-making and determining whether or not there is a risk to the exposed population.

In Ghana, there are no clearly defined national standards for heavy metals in food. The lack of local regulatory standards introduces uncertainty in benchmark comparisons. For fish and food crops, thresholds were drawn from WHO, FAO, EU, and Chinese standards for this study. Studies often use limits established by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) as reference points. These reference values use µg of contaminant/kg body weight. This kind of risk estimation takes food consumption patterns into account. These reference limits cannot be directly compared with laboratory results, as the concentrations are expressed in total mg/kg. A more detailed analysis would be required to determine the true impact of the data obtained, still so they may not reflect local dietary patterns, exposure frequencies, or risk tolerances in Ghana.

Bioavailability and exposure pathways were not assessed. Soil contamination does not directly translate into human exposure without information on bio accessibility, land use, or consumption behaviors. Similarly, elevated levels in fish or crops require contextualization by consumption frequency and demographics.

Future studies should incorporate representative sample size, metal speciation, repeated temporal sampling, biomonitoring of exposed population and exposure modeling to provide a more comprehensive risk analysis.

Chapter 7 CONCLUSIONS AND RECOMMENDATIONS

- Mercury levels in soil were alarmingly high in certain locations within the Ashanti Region, particularly at Konongo Odumase site (mean: 31.01 ppm, max: 909 ppm) and Konongo Zongo (mean: 56.40 ppm, max: 1,342 ppm), especially in areas associated with ore crushing and amalgam burning, suggesting intense historical or ongoing artisanal gold mining activities. These concentrations exceed typical background levels and pose serious risks to both human health and the environment. At these concentrations, the risk of methylation in water affecting fish and food is quite high. In contrast, the Central and Eastern Regions (Akwaboso, Asiakwa, Osino) showed relatively low mercury levels (under 2 ppm). This could be attributed to the predominance of alluvial mining in these areas. Observations from the field revealed miners used less mercury during washing of the ore compared to areas such as the Ashanti region where mercury was added to the ore during crushing, washing, and the amalgamation process.

- Lead contamination followed a similarly concerning pattern. Out of range high maximum concentrations were recorded in the Savannah Region, particularly at the Dakrupe site, and in the Western Region. Such values point to potential risks of lead exposure, especially for nearby communities. Meanwhile, several other sites (e.g. Tinga, Akwaboso, Asiakwa) recorded notably lower Pb levels, reflecting either limited industrial activity or more effective environmental controls.

- Arsenic concentrations were particularly elevated in the Ashanti Region (max 10,060 ppm), with representative values elevated across all sampled locations. In order to assess the health risks associated with the consumption of fish and other food, further analysis is necessary. Such analysis should include the speciation of fish and food samples particularly in Konongo in the Ashanti region. Overall, the data underscores the urgent need for remediation strategies, health risk assessments, and stronger regulatory oversight in highly affected regions.

- Cadmium levels were generally low in soil, staying below reporting limits. However, elevated levels were found in water and fish, especially at Akwaboso, where fish cadmium reached 2.73 mg/kg well above safe limits. This suggests bioaccumulation risks and highlights the need for monitoring water sources and aquatic food chains.

Some food samples, vegetables such as kontomire and pumpkin leaves might pose the highest heavy metal concentration to multi-metal contamination, especially in Western Region and Ashanti Region. Mercury and arsenic levels in these vegetables exceed FAO/WHO safety limits, suggesting possible chronic exposure risk if consumed regularly. Further analysis, like food and fish speciation (mercury, arsenic) is needed to assess the health risks from eating these foods and fish. Fruits and cereals present the lowest contamination levels, making them safer options in these regions.

This study highlights significant contamination from heavy metals, particularly mercury, arsenic, lead, and cadmium, across multiple environmental media; air, soil, water, fish, and food crops in regions affected by artisanal and small-scale gold mining (ASGM) in Ghana. The findings confirm the pressing need for coordinated, long-term strategies to manage environmental pollution and protect public health. To effectively address these challenges, **our study recommends the following to help protect public health.**

Capacity building must be prioritized as a foundational step in mitigating the impacts of heavy metal pollution. This includes training environmental officers, health personnel, and community leaders in the use of portable analytical tools (e.g., XRF, Jerome analyzers) and laboratory-based methods such as ICP-MS as well as the procurement of XRF for EPA's assessment and monitoring purposes. Enhancing local technical expertise will enable more frequent and reliable data collection, improve the quality of environmental assessments, and promote faster responses to pollution events.

Also, the implementation of comprehensive human biomonitoring for residents, especially children and pregnant women, in high-risk areas particularly the Ashanti region, by assessing exposure through hair, blood, and urine samples. To address the complex and potentially synergistic health effects of co-occurring arsenic and other heavy metals in the Ashanti Region's mining-affected areas, we specifically recommend a dedicated sub-study of further assessment of Hg and As in the environmental media (including speciation analysis) and utilizing bioassays to evaluate the biological impact of these exposures.

In addition, focus educational activities and awareness campaigns in the Ashanti Region on promoting mercury-free gold processing methods, specifically targeting the reduction and elimination of mercury use during ore crushing, washing, and amalgamation, given observed differences in mercury application compared to other regions.

Furthermore, increasing the availability and accessibility of environmental data will support more transparent and evidence-based policymaking. Establishing a centralized, open-access environmental database would allow stakeholders including communities, researchers, and regulators to track pollution levels over time and across regions. Such transparency can facilitate targeted interventions, inform public awareness campaigns, and support legal enforcement against polluting activities.

A robust and sustained monitoring framework is essential. This includes expanding the spatial and temporal scope of sampling, incorporating both dry and wet season measurements, and emphasizing the identification of bioavailable and toxic forms of metals (e.g., methylmercury and inorganic arsenic). Regulatory bodies should be equipped not only with better tools but also with the institutional authority and resources to act on pollution findings, including enforcing existing environmental laws and introducing updated standards for food, water, and air quality where necessary.

In conclusion, strengthening environmental monitoring and building local capacity are not only scientific imperatives but also practical strategies to empower communities, reduce exposure risks, and ensure sustainable development. A holistic, multi-stakeholder approach combining technical training, community engagement, data transparency, and policy enforcement will be crucial for mitigating the long-term health and ecological impacts of heavy metal contamination in ASGM-affected regions.

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Appendix A Table of Heavy Metal Concentration in Food

Region	Site	Food	# Samples	Hg				Pb				Cd				As			
				Av	Max	Min	SDv	Av	Max	Min	SDv	Av	Max	Min	SDv	Av	Max	Min	SDv
AR	KZ	Fruit	13	0.15	2.0	<RL	0.55	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.40	3.50	<RL	1.02
		Tuber	3	0.33	1.0	<RL	0.58	0.33	1.00	<RL	0.58	<RL	<RL	<RL	<RL	6.27	18.20	0.10	10.34
		Vegetable	3	<RL	<RL	<RL	<RL	1.00	3.00	<RL	1.73	<RL	<RL	<RL	<RL	7.53	19.60	1.40	10.45
	NY	Fruit	9	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.13	1.00	<RL	0.33
		Tuber	2	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	1.30	1.30	1.30	<RL
		Vegetable	3	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.63	1.00	<RL	0.55
CR	AK	Fruit	2	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.05	0.10	<RL	0.07
		Tuber	1	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	0.10	0.10	0.10	-
		Vegetable	2	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.15	0.30	<RL	0.21
ER	AS	Cereal	2	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.10	0.20	<RL	0.14
		Fruit	11	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.20	2.00	<RL	0.60
		Tuber	4	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
		Vegetable	7	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.14	0.50	<RL	0.20
	OS	Cereal	3	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.07	0.20	<RL	0.12
		Fruit	9	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.26	0.90	<RL	0.30
		Legume	1	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	0.20	0.20	0.20	-
		Rhizome	1	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	0.20	0.20	0.20	-
		Tuber	3	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
		Vegetable	1	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-
SR	DA	Cereal	2	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL

		Fruit	5	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.06	0.20	<RL	0.09
		Legume	1	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-
		Tuber	1	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-
		Vegetable	4	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	0.60	1.00	0.10	0.37
	TA	Fruit	1	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-
		Tuber	2	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
		Vegetable	7	0.29	1.0	<RL	0.49	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
WNR	LA	Cereal	2	<RL	<RL	<RL	<RL	0.30	0.40	0.20	0.14	<RL	<RL	<RL	<RL	0.25	0.50	<RL	0.35
		Fruit	6	0.50	1.0	<RL	0.55	0.17	0.30	0.10	0.10	<RL	<RL	<RL	<RL	0.05	0.30	<RL	0.12
		Tuber	2	<RL	<RL	<RL	<RL	0.25	0.50	<RL	0.35	<RL	<RL	<RL	<RL	1.10	2.10	0.10	1.41
		Vegetable	3	3.33	4.0	2.0	1.15	0.77	1.20	0.50	0.38	<RL	<RL	<RL	<RL	1.40	2.10	0.50	0.82
WR	AC	Cereal	2	<RL	<RL	0.0	<RL	0.10	0.20	<RL	0.14	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
		Fruit	5	<RL	<RL	0.0	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
		Tuber	1	<RL	<RL	0.0	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-	<RL	<RL	<RL	-
		Vegetable	2	<RL	<RL	0.0	<RL	1.60	3.10	0.10	2.12	<RL	<RL	<RL	0.00	9.30	17.20	1.40	11.17
	WK	Fruit	6	<RL	<RL	0.0	<RL	<RL	<RL	<RL	<RL	0.07	0.40	<RL	0.16	0.08	0.20	<RL	0.08
		Tuber	4	<RL	<RL	0.0	<RL	0.13	0.50	<RL	0.25	0.30	1.20	<RL	0.60	0.15	0.30	<RL	0.13
		Vegetable	6	1.00	2.0	0.0	1.10	0.18	0.40	<RL	0.16	<RL	<RL	<RL	<RL	0.27	1.60	<RL	0.65

RL = reporting limit, SD = standard deviation, AV = mean, min = minimum, max = maximum
red = above maximum levels of WHO/FAO and/or European Union and/or Chinese Standard (FAO & WHO, 1995; European Commission, 2023; USDA, 2018)

Appendix B Additional Figures

Figure B.1: Arsenic in Soil at Konongo Zongo

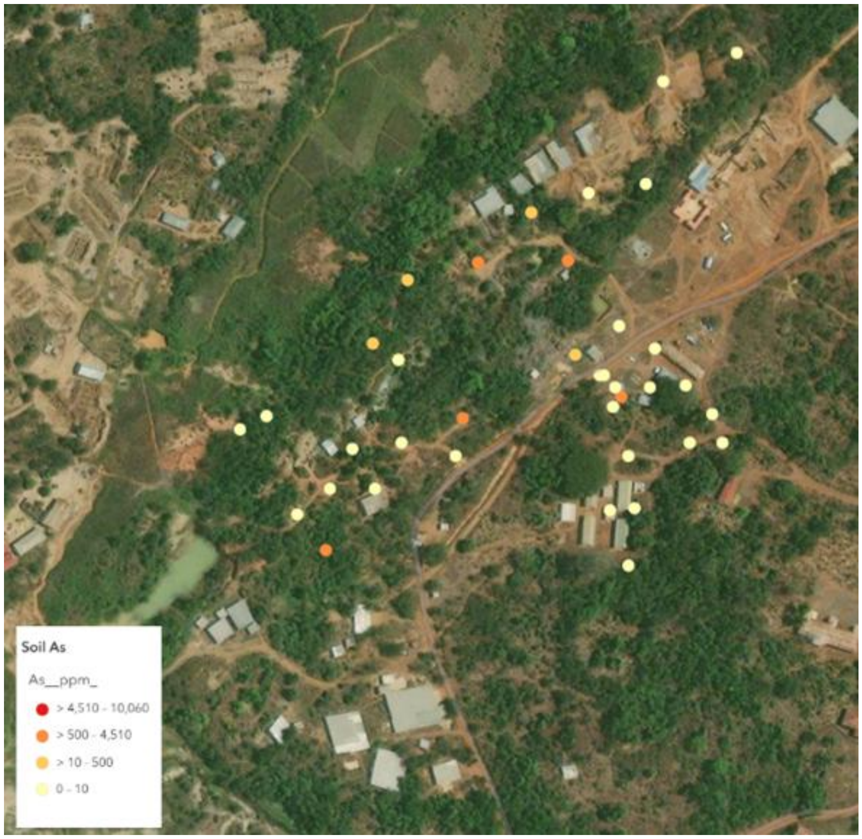

Figure B.2: Arsenic in Soil at Konongo Odumase

Figure B.3: Mercury in Soil at Lake Amponsah