

Environmental Contamination and Exposure Pathways of Toxic Metals in ASGM Areas in Ghana: A Multi-Regional Assessment

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“Environmental Contamination and Exposure Pathways of Toxic Metals in ASGM Areas in Ghana: A Multi-Regional Assessment”

Abstract

Artisanal and small-scale gold mining (ASGM) is both a major source of livelihood and of toxic metal environmental contamination in Ghana. While prior studies in the country have focused on mercury, less is known about the combined distribution and exposure risks of multiple toxic metals across environmental media and food systems. This study is the first multi-regional assessment of mercury, lead, arsenic, and cadmium across eleven ASGM sites in six regions of Ghana. A combination of field-based rapid screening (X-ray fluorescence [XRF], Jerome® mercury vapor analyzer) and laboratory analysis with inductively coupled plasma mass spectrometers (ICP-MS) and inductively coupled plasma-optical emission spectrometer (ICP-OES) was used to quantify contamination in soil, water, air, selected crops, and fish. Soil contamination in the Ashanti and Western regions exceeded international thresholds for lead, mercury, and arsenic, with arsenic levels in one site reaching 10,060 mg/kg. Overall, water contamination was less severe except for Asiakwa, and airborne mercury was mostly below national limits. Food system analysis suggested that soil–crop–dietary transfer may be an important exposure pathway. Several crops and fish samples surpassed WHO/FAO safety limits. Validation of portable XRF measurements against laboratory results showed strong correlations ($r = 0.85\text{--}0.94$), supporting the use of XRF in settings with limited resources. The novel contributions of this study include: the first integrated mapping of toxic metals across multiple media in Ghana’s ASGM areas; empirical evidence of food-chain bioaccumulation as a critical exposure route; and the demonstration of cost-effective, field tools for large-scale monitoring. These findings provide essential evidence for Ghana’s policy response under the Minamata Convention and highlight the need for region-specific mitigation strategies.

Keywords

Artisanal mining; mercury; lead; arsenic; food safety; public health

1. Introduction

Overview of ASGM in Ghana

Artisanal and small-scale gold mining (ASGM) is a significant socio-economic activity in Ghana. It provides employment and income to a large segment of the population, particularly in rural and resource-dependent communities (Achina-Obeng & Aram, 2022); it substantially contributes to Ghana’s gold output. However, the environmental impacts of ASGM are profound. Common mining practices lead to the degradation of

natural ecosystems, including contamination of water bodies and food systems and the destruction of soils and vegetation.

Environmental and health concerns related to toxic metals

A central environmental and public health concern related to ASGM is the widespread use of mercury. Mercury amalgamates with gold and is released into the air when this amalgam is burned. Methods such as whole ore amalgamation and open or enclosed burning contribute to mercury exposure among miners, their families, their communities, and the environment (Mantey et al., 2020). Mercury can contaminate air, water, soil, and food sources, and exposure to mercury presents severe health risks, including neurological disorders and developmental impairments (Fowler & Zalups, 2022). Vulnerable groups, such as children and pregnant women, are particularly at risk (Ha et al., 2017).

In addition to mercury, ASGM activities mobilize other toxic heavy metals, including arsenic, cadmium, and lead, which occur naturally in ore-bearing rocks (Saunders et al., 2013). Crushing, grinding, and sediment washing release these elements into the surrounding environment, where they accumulate in soils, surface waters, and vegetation. These metals persist in the environment and can be absorbed by agricultural products, especially root and tuber crops, such as cassava and cocoyam, but also can be absorbed in less degree by fruit such as plantain (Bortey-Sam et al., 2015; Nkansah et al., 2021; Obiri et al., 2016; Opoku et al., 2024). The health implications of chronic exposure to these metals are well documented. Arsenic is a carcinogen that affects skin, bladder, and lung tissues and disrupts cellular respiration. Cadmium accumulates in the kidneys, leading to tubular dysfunction, bone demineralization, and cardiovascular issues. Lead impairs heme synthesis and neurodevelopment, leading to cognitive deficits in children, as well as hypertension and cardiovascular diseases in adults (Jomova et al., 2025; Larsen & Sanchez-Triana, 2023; Nordberg & Costa, 2021). The cumulative effect of dietary exposure, particularly in farming communities reliant on potentially contaminated food and water sources, heightens the risk (Marchese et al., 2024).

Gaps in previous assessments (regional, food-chain, exposure pathways)

Ecologically, toxic metal contamination disrupts aquatic and terrestrial ecosystems, reduces biodiversity, and compromises the fertility of agricultural lands (Hama Aziz et al., 2023; Khushbu et al., 2022). These consequences threaten food security and rural livelihoods. The persistent nature of these contaminants means that their harmful effects may last for decades after mining operations cease (Opoku et al., 2024).

Despite national commitments under international frameworks, specifically the Minamata Convention on Mercury, there remain critical data gaps (United Nations Environment Programme, 2013). These include regional disparities in heavy metal contamination levels, limited understanding of food-chain transfer dynamics, and inadequate assessments of exposure pathways. Furthermore, prior studies have not always covered multiple environmental media or incorporated community-level insights and dietary assessments.

Study aim: comprehensive assessment of environmental contamination, exposure routes, and public health implications

This study addresses these gaps by conducting a comprehensive environmental contamination and exposure assessment of toxic heavy metals in ASGM areas across Ghana.

1.2 Objectives

General Objective

The study's primary objective was to assess toxic heavy metal pollution in eleven ASGM sites across six mining regions in Ghana using environmental sampling and analysis across multiple media: air, water, soil, fish, and food crops. The metals of interest were mercury (Hg), lead (Pb), cadmium (Cd), and arsenic (As).

Specific Objectives

Specific study objectives were to (1) define the geographical boundaries of each study site through GPS mapping, surrounding land use features, and proximity to potential contamination pathways; (2) quantify concentrations of Hg, Pb, Cd, and As in soil, air (only Hg), surface and groundwater, fish, and food crops; and (3) advance the understanding of toxic metal contamination pathways and their interaction with food systems.

1.3 Study Scope

The study integrated environmental measurements to capture a comprehensive picture of toxic metal contamination and exposure:

- Sampling and analysis of air (for Hg), soil, surface and groundwater, fish, and food crops (e.g., grains, vegetables, fruits).
- Quantification of Hg, Pb, Cd, and As levels.
- Identification of contamination sources, including mining activities.
- Comparison of observed concentrations with national and international threshold values and guidelines.

2. Materials and Methods

2.1 Study Design

This study employed a multi-region, cross-sectional field design targeting eleven ASGM sites in six regions of Ghana: Eastern, Western, Ashanti, Savannah, Central, and Western North (**Table 1**). The selection aimed to capture environmental and public health risks associated with different ASGM typologies across

ecological, residential, and agricultural zones. **Figure 1** shows the general distribution of ASGM sites in Ghana (adapted from Takyi et al., 2021 and highlights the specific study locations. See **Figures B1–B8** for supplementary descriptions of the evaluated areas in the six regions included in the study).

Environmental sampling focused on five media: soil, air (for mercury only), water, fish, and food crops. The study was conducted between August 2024 and July 2025.

Table 1 Study sites and corresponding regions

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)

2.2 Sampling and Instruments

2.2.1 Desk Review and Site Selection

A preliminary desk review informed site prioritization and guided risk hypotheses development. Data sources included the Toxic Sites Identification Program (TSIP) Database (<http://www.contaminatedsites.org>), environmental impact assessments, Ghana Environmental Protection Authority (EPA) records, and published literature (Saim, A. K. 2021; Rajaei et al., 2015; Ofosu-Asiedu et al., 2013; Alhassan et al., 2022; Ovadje et al., 2021; Akabzaa et al., 2009; Boateng, 2018; Duncan, 2020; Asamoah, 2012). Sites were selected based on evidence of past or ongoing ASGM activity; reported mercury use; accessibility; and proximity to residential, agricultural, or aquatic areas.

2.2.2 TSIP Methodology-Based Training and Protocol Development

Before field deployment, a training workshop was held with field researchers, representatives from the Ghana EPA and the Ministry of Environment, Science, and Technology (MEST), and the Pure Earth Ghana team. The training covered TSIP methodology, safety protocols, standardized field instrumentation and data collection procedures, and stakeholder engagement techniques. The training also included practical sessions and a pilot visit to Kyebi, a historically significant ASGM area.

2.2.3 Field Screening Instruments

X-Ray Fluorescence (XRF) Analysis. Soil samples were analyzed in situ using portable XRF spectrometers to quantify trace and toxic metals. The XRF technique was chosen for its rapid response and field-proven accuracy for environmental screening (U.S. EPA, 2007). Each environmental sample was measured for at least 30 seconds using the XRF analyzer, following a standardized protocol for preparation.

Two handheld analyzers were used: a Thermo Scientific Niton™ XL3T 700S (Thermo Portable Analytical Instruments Inc., Billerica, MA, USA; Detector Model: RadEye; S/N 118610; Calibration: Aug 17, 2021; Software 8.L.28) and an Olympus Vanta™ VCR (Olympus Corp., Tokyo, Japan; 40 kV, 0.2 mA; S/N 803956). Both operated in “Soil” mode for element screening. Limits of detection (LOD) under soil mode were 9 ppm for Hg, 8 ppm for Pb, 12 ppm for Cd, and 7 ppm for As, consistent with manufacturer specifications and prior validation studies for portable XRF analyzers (U.S. EPA, 2012; Thermo Scientific, 2021; Olympus Corp., 2018).

Jerome® 431-X Mercury Vapor Analyzer. The study utilized a Jerome® analyzer, which is designed to detect and quantify concentrations of mercury vapor in ambient air. The instrument has a LOD of 0.003 mg/m³ (3 µg/m³), enabling its use for occupational exposure monitoring and environmental site assessments (Arizona Instrument LLC, 2012).

2.3 Sampling and Exposure Assessment

2.3.1 Soil Sampling

Soil was collected from depths of 0–15 cm at multiple points across each site, using a stainless-steel auger and following a coning and quartering method to ensure representativeness and avoid cross contamination. Composite samples ($n \geq 3$ subsamples per site) were air-dried, homogenized, and stored in clean, labeled polyethylene bags. Sampling site GPS coordinates were recorded for spatial mapping. At least eight XRF measurements of 30 seconds each were taken per sample. Subsamples were sent for confirmatory Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) analysis.

2.3.2 Water Sampling

Surface water (e.g., from rivers and streams) upstream and downstream, as well as groundwater (i.e., from boreholes and wells) were sampled from mining sites. Samples were collected mid-stream at mid-depth, acidified with ultrapure nitric acid (HNO_3), and stored in pre-cleaned 250 mL HDPE bottles. Total and dissolved metal fractions were distinguished using 0.45 μm membrane filters.

2.3.3 Food Crop Sampling

Crops were selected based on local dietary importance and proximity to contaminated areas. Sampling included leafy vegetables (such as *kantomire* [cocoyam leaves], pumpkin leaves), fruits, tubers, rhizomes, and cereals. Edible and non-edible parts were collected, washed with distilled water, air-dried at $<40^\circ\text{C}$, and stored in labeled paper bags. Representative composite samples were digested and analyzed for toxic metals.

2.3.4 Fish Sampling

Fish were sampled from rivers or ponds adjacent to ASGM sites, following local fishing regulations and ethical standards (Ghana EPA, 2012; Mason et al., 2019). A maximum of seven fish per site were collected to account for biological variation. The samples included tilapia, catfish, and mudfish. The samples were acquired with the assistance of local fishermen and community members using traditional gear and ensuring compliance with permissions granted. Length and weight were recorded for age estimation. Samples were stored on ice and transported to the laboratory, where the edible portions were dissected and prepared for toxic metal analysis.

2.3.5 Air Sampling (mercury only)

Mercury vapor concentrations were measured at each ASGM site and surrounding residential areas using the Jerome® analyzer under typical operating conditions. Each reading lasted at least 30 seconds to ensure stability, and GPS coordinates were recorded for spatial mapping.

2.4 Laboratory Analysis and Quality Assurance

All laboratory protocols followed international standards (American Public Health Association [APHA], United States Environmental Protection Agency [U.S. EPA] analytical methods) and included certified reference materials, blanks, and duplicate samples at a rate of 1 per 10 samples. Confirmatory soil samples, as well as water, food, and fish specimens, were analyzed at the ISO-certified SGS Laboratory in Tema, Ghana, which holds CLA Testing Certification No. A3699.

Two analytical methods were used. ICP-MS was applied for ultra-trace metals and metalloids in water, food, and biological samples, and ICP-OES was used for multi-element analysis of soil and plant matrices, offering a wide dynamic range for major and minor elements. For methodological details, please see Supplement.

2.4.1 Soil and Crops/Food

Samples were prepared according to U.S. EPA 3050B for acid digestion using concentrated nitric acid (HNO_3) and hydrochloric acid (HCl). After digestion and dilution with deionized water, samples were analyzed using ICP-MS and ICP-OES. Results were reported in mg/kg (dry weight).

2.4.2 Water

Water samples were analyzed for major cations and trace metals using ICP-MS and ICP-OES, following methods of APHA 3120, as well as U.S. EPA 200.7 and 200.8. Acidified samples were digested for total metal analysis. Metal concentrations were reported in mg/L.

2.4.3 Fish

Fish tissue was digested using a sequential acid method (HNO_3 and H_2O_2) per U.S. EPA 200.3 and 200.8. Metal concentrations were expressed in mg/kg (wet weight), adjusted based on sample moisture content.

2.5 Data Processing and Statistical Analysis

For results below the reporting limit (RL) of the laboratory, values were substituted with $\text{RL}/\sqrt{2}$. The reporting limits are listed in **Table A1**.

Descriptive statistics (mean, median, standard deviation, range) were computed for each environmental medium-metal pair. Histograms and quantile-quantile (Q-Q) plots were used to assess data normality. Spatial interpolation and contamination mapping were conducted using the geostatistical tools available in ArcGIS Pro Online (ESRI), applying Inverse Distance Weighting (IDW) and kriging techniques to generate spatial distribution maps of contamination.

To examine regional differences in toxic metal concentrations across environmental media, Jonckheere-Terpstra trend tests (JT) were conducted, with regions treated as an ordered factor based on geographic progression.

In addition to correlation analyses between field-based and laboratory-based measurements, method validation was conducted by comparing portable XRF data with reference laboratory values. Pearson's correlation coefficients (r) were calculated to assess linear relationships, and recovery rates were computed to evaluate measurement accuracy. Furthermore, JT trend tests were applied to detect ordered differences in toxic metal concentrations across regions and media (soil, water, air, fish, food crops). Additional analysis was done to know if higher location-level soil Hg is associated with higher food Hg concentrations. Food samples were combined for the measurements of vegetables, fruit, tuber, cereal, rhizome, and fish. For each location, we summarized soil Hg as the geometric mean of soil samples and joined this value to all food samples from the same region–location pair. Reported values under RL were set to RL. We examined whether higher location-level Hg or As levels in soil was associated with higher Hg or As levels in foods. Food samples (vegetable, fruit, tuber, cereal, rhizome, fish) were pooled as “food”. To stabilize skew while retaining zeros, we modeled food Hg and food As on the log1p scale. We fit a generalized additive model with parametric terms for $\ln_soil_c$ and food type and a random intercept for region. Data analyses were performed in R 4.4.2 (mgcv), and mapping/spatial work in QGIS 3.40.

2.6 Reference, Guidance, and Threshold Levels

Threshold limits are more legally enforceable than guidance, review, or reference values when assessing the risk of results from environmental samples. The others serve as advisory benchmarks to support risk assessments.

This study used Ghanaian reference values, where possible, to compare results. For Ghana, reference values were available for air and water (Ghana EPA, 2019; Ghana Standards Authority, 2024). Otherwise, we identified values suggested by other authorities and regulatory agencies:

- Maximum levels of contaminants by the United Nations Food and Agriculture Organization (FAO) and the World Health Organization (WHO) (FAO & WHO, 2023; FAO & WHO, 2024)
- Residential soil guidance values by U.S. EPA (U.S. Environmental Protection Agency, 2024)
- German review values for the soil-human pathway for housing areas and children's play areas. We applied those values since children were observed playing within contaminated sites. The soil level for lead is identical with the revised U.S. EPA value (BMUV, 2021)
- European Commission regulations regarding maximum permissible levels for specific contaminants in food (European Commission, 2023) and mercury (European Commission, 2018)
- China Standards for Maximum Levels of Contaminants (U.S. Department of Agriculture-Foreign Agricultural Service, 2018)

Table 2 summarizes reporting thresholds for selected metals across air, water, and soil. **Table 3** provides international benchmark values for contaminants in fish and food products, against which results were interpreted.

Table 2 Reference values for air, water, and soil (reporting/guidance values)

	Air (ng/m³)	Water (mg/L)	Soil for residential areas (ppm)	Soil for housing areas (ppm)	Soil for playgrounds (ppm)
	Ghana (Ghana EPA, 2019)	Ghana (GSA, 2024), FAO & WHO (FAO & WHO, 2023)	U.S. EPA (U.S. Environmental Protection Agency, 2024)	Germany (BMUV, 2021)	Germany (BMUV, 2021)
Arsenic	15	0.01	35	50	25
Cadmium	3	0.003	7.1	20	10
Lead	0.5	0.01	200	400	200
Mercury	15 ng/m ³ for 24 hours averaging 1 µg/m ³	0.001	7.1	20	10

Table 3 Maximum levels (mg/kg) for contaminants in fish and food

	Fish	Fruit	Tuber	Vegetable	Cereal	Legume	Rice
Arsenic	0.1 [#]	0.5 ^{\$}	0.5 ^{\$}	0.5 [#]	0.5 [#]	0.5 ^{\$}	0.2–0.35 ⁺
Cadmium	0.05 ⁺	0.1 ⁺	0.1 ⁺	0.05 ^{+, &}	0.1 ⁺	0.1 ⁺	0.4 ⁺
Lead	0.3 ⁺	0.1 ⁺	0.1 ⁺	0.05 ^{+, %}	0.2 ⁺	0.1 ⁺	0.5 [#]
Mercury	0.5 ⁺	0.01 ^{\$}	0.01 ^{\$}	0.01 ^{#, \$}	0.01 ^{\$}	0.01 ^{\$}	0.02 [#]

(+) WHO/FAO (FAO & WHO, 2023, 2024)

(*) EU Commission (European Commission, 2023)

(#) China Standards (U.S. Department of Agriculture-Foreign Agricultural Service, 2018)

(\$) EU Commission for mercury (European Commission, 2018)

(\$) proxy value: for arsenic, we applied the same limits for fruit, tuber, and legume as for vegetables and cereals.

(&) For cadmium, there are different max. levels for different types of vegetable from 0.05 to 0.2. Due to the precautionary principle, 0.05 was used for the statistical analysis.

(%) For lead, there are different max. levels for different types of vegetable from 0.05 to 0.3. Due to the precautionary principle, 0.05 was used for the statistical analysis.

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

2.7 Ethical Considerations

All sampling activities followed local environmental and ethical guidelines. Prior to fieldwork, permissions were obtained from the Ghana EPA, the respective District Assemblies, and local community leaders. Environmental media sampling was conducted with the informed consent of household participants and local farmers, ensuring voluntary participation and transparency about the study objectives. Soil, fish, and crop sampling complied with regulations from the Ghana EPA, the Ghana Food and Drugs Authority, and the Ministry of Fisheries.

3. Results

3.1 Tool Effectiveness: Correlation between XRF and Laboratory-Based Measurements

A total of 1,040 soil measurements were conducted for the four selected employing portable XRF analyzers as the primary instrument for analysis. A total of 115 confirmatory samples (each measured 8 times using the XRF) were dispatched for laboratory ICP-MS analysis to validate the results and ascertain correlation. After eliminating the samples below the relevant LOD or RL, a total of 37 samples were included in the correlation analysis (see **Table 4** and **Figure B11**). The correlation between the XRF and laboratory-based measurements was high and statistically significant for the three most relevant metals (i.e., Pearson's correlation coefficient was $r = .85$ for Hg, $r = .92$ for Pb, and $r = .94$ for As; all 95% confidence intervals excluded zero, confirming the significance of these correlations). Soil was generally below detection limit by XRF testing and ICP-MS for Cd, so no correlation analysis was performed.

The geometric mean (GM) concentrations measured by XRF in tested soil samples were 23.21 ppm for Hg, 23.34 ppm for Pb, and 229.61 ppm for As. Corresponding laboratory-based values were higher for Hg (35.99 ppm) and Pb (27.23 ppm), while As values were comparable (225.17 ppm). The mean recovery rates (i.e., the ratio of the concentration measured by the analytical method to the known or reference concentration) for XRF relative to ICP-MS values were 70.82% for Hg, 92.60% for Pb, and 125.81% for As, with corresponding median recovery rates of 71.02%, 81.94%, and 85.40%, respectively.

XRF data were validated by comparing results with ICP-MS measurements. Correlation coefficients (Pearson's r) were calculated for all study metals (As, Pb, Hg, Cd). Field values were used primarily for rapid risk assessment and hotspot mapping. Due to skewed distributions and censoring below detection limits, medians were used in summary statistics.

Table 4 Correlation analysis between XRF and ICP-MS for soil

Element	N	r	95% CI (r)	GM XRF	GM Lab	Mean Recovery (%)	Median Recovery (%)
Hg	37	.852	[.730, .922]	23.21	35.99	70.82	71.02
Pb	37	.919	[.847, .958]	23.34	27.23	92.60	81.94
As	37	.942	[.890, .970]	229.61	225.17	125.81	85.40

Note: GM = Geometric Mean; CI = Confidence Interval

Our elevated recovery rate for As (see **Table 4** and **Figure 2**) may indicate systematic overestimation by the XRF device, while the lower recovery for Hg suggests a potential underestimation in field conditions. Overall, the data support the use of portable XRF as a valid screening tool in field conditions, particularly when rapid or non-destructive analysis is prioritized.

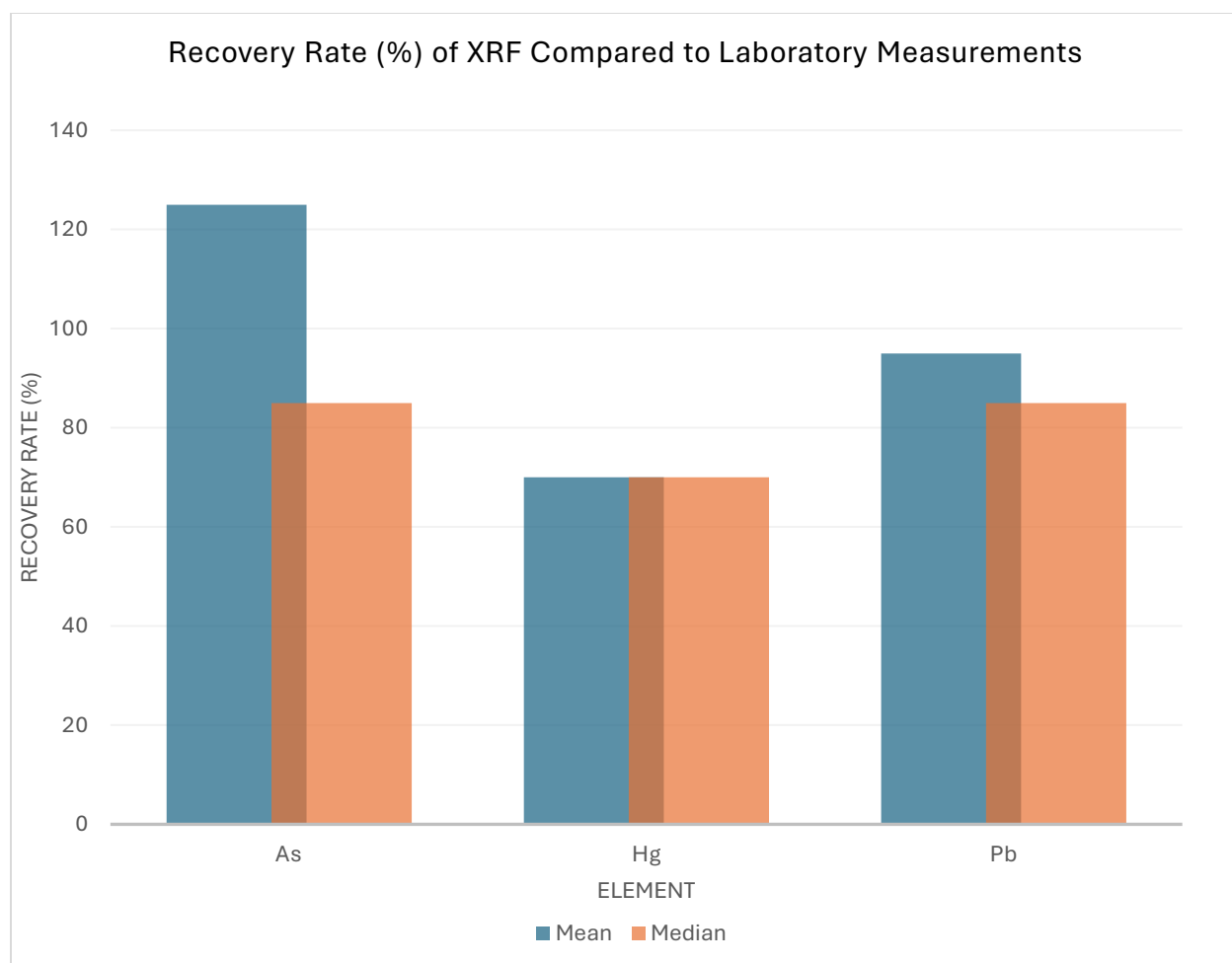


Figure 2. Recovery rate (%) of XRF compared to laboratory measurements

3.2 Descriptive Analysis of Toxic Metal Contamination in ASGM Areas in Ghana

In air, 1,045 mercury vapor concentrations were measured using the Jerome® analyzer. Concentrations were generally below Ghana's permissible limit of 1 $\mu\text{g}/\text{m}^3$, except at Wassa Kayianko (WK), where the mean was 1.84 $\mu\text{g}/\text{m}^3$ and the maximum reached 150.2 $\mu\text{g}/\text{m}^3$ (see **Table A2**. For Hg vapor distribution per site, see **Figure B9**.)

In soil, metal levels varied considerably (see **Table 5** and **Figure B12**). A total of 1,040 readings were taken with XRF analyzers across all sites to determine the concentration of metals in soil. Cd was the only metal with all results below the RL. The reference values for comparison are: 10 ppm for Hg (German soil protection regulation values for children's play areas; (BMUV, 2021)), 200 ppm for Pb (U.S. EPA values for residential soil; (U.S. EPA, 2024)), and 25 ppm for As (German soil protection regulation values for children's play areas; (BMUV, 2021)). The results for Hg, Pb, and As are shown in **Table 5**. The highest mean Hg concentration was 56 ppm in Konongo Zongo (KZ). Mean levels of concern were also observed

in Konongo Odumase (KO) at 31ppm and Ankobra Community (AC) at 12 ppm. The Pb concentration average per site did not exceed the selected reference value. Dakrupe (DA) in the Savannah Region was the site with the highest mean Pb concentration at 48 ppm; the highest individual measurements recorded were at the Dakrupe site with 3,899 ppm, substantially higher than the reference value of 200 ppm. As had the highest concentrations compared to the reference level, with 8 out of the 11 sites tested sites reporting higher than the reference value. Konongo Zongo had the highest mean As concentration at 1,066 ppm, which is more than 40 times the reference value; Konongo Zongo also had the highest recorded single measurement at 10,060 ppm, more than 400 times the reference value. The soil results indicate that many measurements exceeded guideline values and highlight severe contamination hotspots, particularly in Konongo Zongo, Nyamebekyere (NY), and Dakrupe.

A total of 69 water samples were submitted for laboratory analysis of Hg, Pb, Cd, and As. While the majority of analytical results were below the corresponding Ghanaian regulatory standards, elevated concentrations exceeding the applicable limits were detected in several samples (see **Table A3** and **Figure B14**). The analysis revealed Hg levels that exceeded the permissible limit in multiple water samples (see **Figure B14**). The concentrations of Hg in these samples exceeded the national threshold of 0.001 mg/L, with a maximum concentration of 0.01 mg/L recorded in Asiakwa (AS). Similarly, the analysis revealed Pb levels that exceeded the permissible limit in several water samples, with concentrations that surpassed the national threshold of 0.01 mg/L (see **Figure B14**). The maximum recorded level was 0.97 mg/L in Asiakwa, where over 50% of the water samples were found to be above the established threshold. In three sites (Konongo Odumase, Nyamebekyere, Ankobra), total As concentrations exceeded the national threshold of 0.01 mg/L (see **Figure B14**). The maximum recorded level was 3.30 mg/L in Konongo Odumase. Cd levels in water were generally low; however, the maximum concentration recorded in Asiakwa was 0.0051 mg/L, exceeding the national threshold of 0.003 mg/L.

In fish, a total of 46 samples were analyzed, and toxic metal concentrations showed considerable variability across sites (see **Table A4** and **Figure B15**). Hg levels were generally low and below the regulatory maximum of 0.5 mg/kg, with the highest mean of 0.087 mg/kg measured at Konongo Zongo. In contrast, Pb and Cd exceeded international limits at multiple sites, including Pb measurements of up to 2.80 mg/kg and Cd measurements of up to 2.73 mg/kg at the Akwaboso site in the Central Region. As contamination was also elevated in all study sites, reaching a maximum of 3.09 mg/kg at Konongo Zongo and 2.82 mg/kg at Akwaboso, far above the safety threshold of 0.1 mg/kg. The data distribution indicates a substantial number of samples that exceeded the reference value for Pb, Cd, and As at Akwaboso. As speciation was not performed; only total concentrations were measured. Toxicity depends on chemical species (e.g., inorganic arsenic). This means risk may be overestimated. Though As levels exceeded maximum permissible limits in nearly all sites, it is important to emphasize the elevated concentrations observed in Lake Amponsah (LA) in the Western North Region (WNR) and Ankobra Community (AC) in the Western Region (WR).

Food crop data (**Table 6**) showed generally relatively lower levels of contamination, with Hg and Pb results often below reporting limits; however, some elevated values were observed. The highest reported Hg concentrations (4 mg/kg) were found in two vegetables in the Western North Region. Vegetables from the Western Region also had the highest mean Pb concentration (3.1 mg/kg). The highest mean As concentration was 19.600 mg/kg found in vegetables from the Ashanti Region and was also elevated in fruits from the Ashanti Region. Toxicity depends on specific species: methylmercury and inorganic arsenic in food pose the greatest risks. However, only total concentrations were measured, which may overestimate hazards. Speciation analysis is needed for accurate risk assessment. Supplementary information by food category for the four analyzed metals is provided in **Tables A5–A9**.

Table 5 Toxic metal concentrations in soil samples (in ppm)

Region	Site	N	Mercury (Hg)				Lead (Pb)				Arsenic (As)			
			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	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	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	AC	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

Note: 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); blue = above review/guidance values of 200 ppm for lead (Residential Soil Guidance Values and German review values for the soil-human pathway for children's

play areas; BMUV, 2021; U.S. EPA, 2024); pink = above review/guidance values of 25 ppm for arsenic (German review values for the soil-human pathway for children's play areas; BMUV, 2021); AC – Ankobra Community, AK – Akwaboso, AR – Ashanti Region, AS – Asiakwa, CR – Central Region, DA – Dakrupe, ER – Eastern Region, KO – Konongo Odumase, KZ – Konongo Zongo, LA – Lake Amponsah, NY – Nyamebekyere, OS – Osino, SR – Savannah Region, TA – Tinga, WK – Wassa Kayianko, WNR – Western North Region, WR – Western Region.

Table 6 Descriptive data for the food crop categories by region

Food	Region	n	Mercury (Hg)				Lead (Pb)				Arsenic (As)			
			Mean	SD	Median	Max	Mean	SD	Median	Max	Mean	SD	Median	Max
Cereal	ER	5	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.122	<RL	<RL	0.200
Cereal	SR	2	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL
Cereal	WNR	2	<RL	0.000	<RL	<RL	0.300	0.141	0.300	0.400	0.285	0.304	0.285	0.500
Cereal	WR	2	<RL	0.000	<RL	<RL	0.135	0.091	0.135	0.200	<RL	0.000	<RL	<RL
Fruit	AR	22	0.779	0.280	<RL	2.000	0.113	0.198	<RL	1.000	1.170	3.884	<RL	18.200
Fruit	CR	2	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.085	0.021	0.085	0.100
Fruit	ER	20	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.264	0.460	<RL	2.000
Fruit	SR	6	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.097	0.052	<RL	0.200
Fruit	WNR	6	0.854	0.160	0.854	1.000	0.167	0.103	0.100	0.300	0.109	0.094	<RL	0.300
Fruit	WR	11	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.090	0.039	<RL	0.200
Tuber	AR	3	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.633	0.611	0.500	1.300
Tuber	CR	1	<RL	N/A	<RL	<RL	<RL	N/A	<RL	<RL	0.100	N/A	0.100	0.100
Tuber	ER	7	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL
Tuber	SR	3	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL
Tuber	WNR	2	<RL	0.000	<RL	<RL	0.285	0.304	0.285	0.500	1.100	1.414	1.100	2.100
Tuber	WR	5	<RL	0.000	<RL	<RL	0.157	0.192	<RL	0.500	0.148	0.100	0.100	0.300
Vegetable	AR	8	<RL	0.000	<RL	<RL	0.437	1.036	<RL	3.000	3.243	6.634	1.150	19.600
Vegetable	CR	2	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.185	0.162	0.185	0.300
Vegetable	ER	10	<RL	0.000	<RL	<RL	<RL	0.000	<RL	<RL	0.175	0.140	0.135	0.500
Vegetable	SR	12	0.756	0.114	<RL	1.000	<RL	0.000	<RL	<RL	0.247	0.326	<RL	1.000
Vegetable	WNR	3	3.333	1.155	4.000	4.000	0.767	0.379	0.600	1.200	1.400	0.819	1.600	2.100
Vegetable	WR	8	1.192	0.669	<RL	2.000	0.555	1.035	0.200	3.100	2.569	5.947	<RL	17.200

Note: RL = reporting limit; SD = standard deviation; Max = maximum; red = above review/guidance values for mercury; blue = above review/guidance values for lead; pink = above review/guidance values for arsenic; AR – Ashanti Region, CR – Central Region, ER – Eastern Region, SR – Savannah Region, WNR – Western North Region, WR – Western Region.

3.3 Regional Patterns and Hotspots of Toxic Metal Contamination in ASGM Areas

JT trend tests were conducted to examine regional differences in toxic metal concentrations across environmental media (**Table ?**). These tests were performed for Hg, Pb, and As, with regions treated as an ordered factor based on geographic progression.

For soil samples, highly significant ordinal trends were observed across regions for all three elements. These results suggest systematic regional differences in soil contamination levels in ASGM areas of Ghana. In water samples, no significant trends were observed for Hg or Pb. A marginally non-significant trend was observed for As. In fish samples, no significant trends were observed for Hg or Pb. For As, a statistically significant trend was observed. In crop samples, no significant trends were observed for Hg, Cd, or As. Only Pb demonstrated a significant directional trend. For air samples, no significant regional trend was found for Hg concentrations.

The regional analysis of soil samples revealed substantial variability in toxic metal concentrations across sites (**Figure 3**). Notably, several locations exceeded reference values. The highest Hg concentrations in soil were observed in Konongo Zongo, with a mean of 56 ppm and a maximum of 1,342 ppm, well above the German threshold of 10 ppm (BMUV, 2021). Elevated Pb levels were found in sites such as Dakrupe (Savannah Region), with a mean of 48.8 ppm and a maximum of 3,899 ppm, surpassing U.S. EPA residential soil guidance values of 200 ppm (U.S. EPA, 2024). As concentrations were particularly high in multiple regions, with the most extreme case in Konongo Zongo (Ashanti Region), showing a mean of 1,066ppm and a maximum of 10,060 ppm. These values confirm the presence of contamination in areas where ASGM activities are developed. These findings also underscore regional disparities in soil contamination, with areas such as the Ashanti Region and Western Region being particularly affected. This spatial heterogeneity highlights the need for region-specific risk assessments and targeted remediation strategies.

A closer look at the regional variation of Hg in food crop samples does not give clear results. Because of fewer values by location, comparison was made on a regional level. Mean values are stable throughout all regions at the minimum value, with higher differences for medians, resulting from some samples with high concentrations. Overall variation within the regions is high, showing no clear regional concentration (see **Figure 4**).

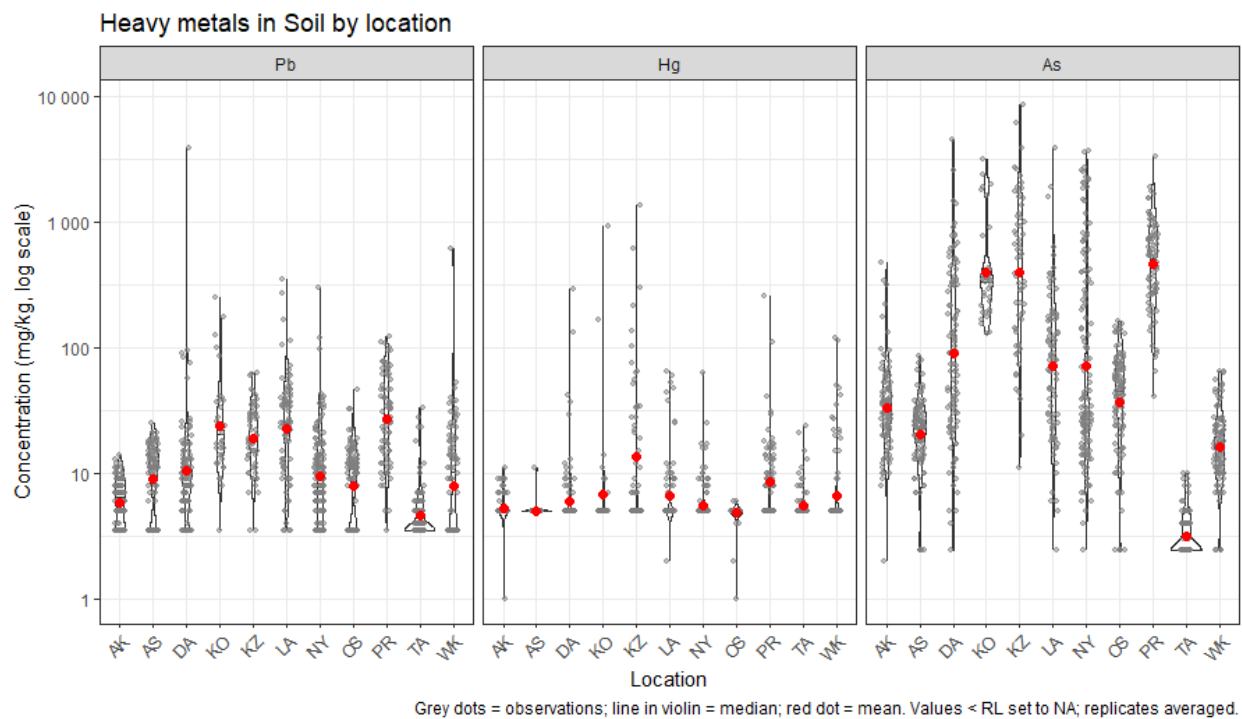


Figure 3. Violin plots of toxic metals (Pb, Hg, and As) in soil by location

Concentration in mg/kg, y-axis – logarithmic scale. AC – Ankobra Community, AK – Akwaboso, AS – Asiakwa, DA – Dakrupe, KO – Konongo Odumase, KZ – Konongo Zongo, LA – Lake Amponsah, NY – Nyamebekyere, OS – Osino, TA – Tinga, WK – Wassa Kayianko

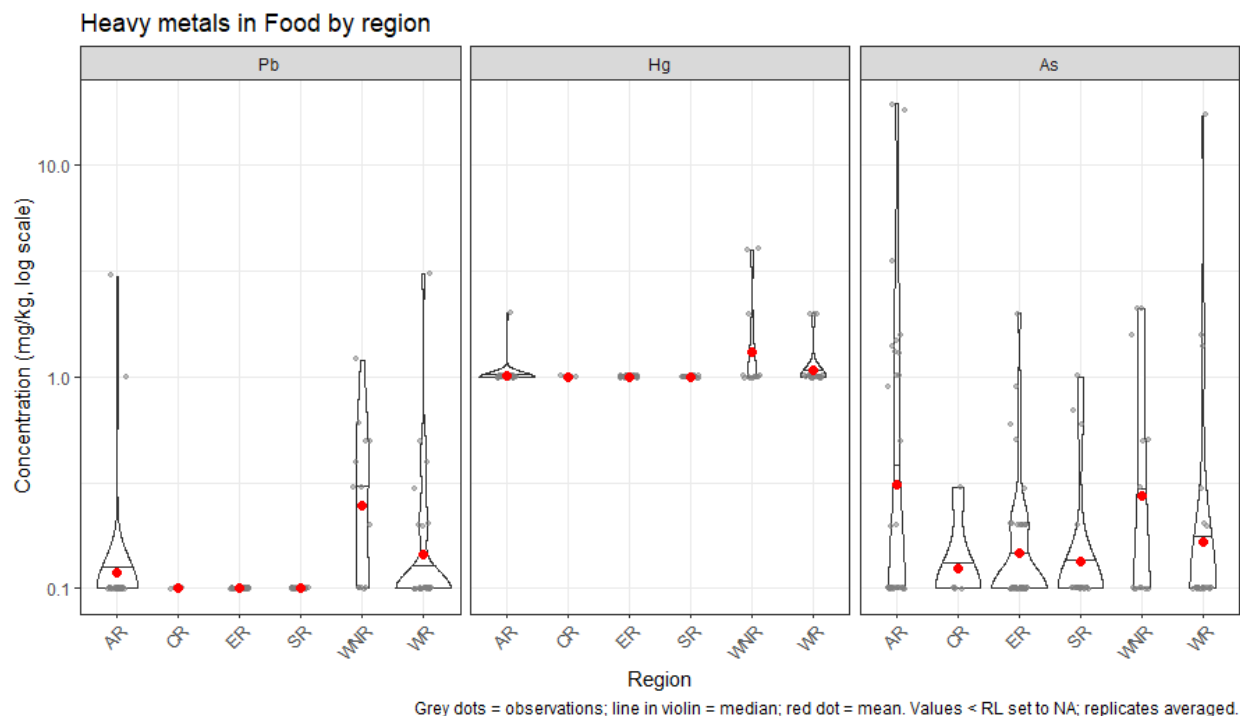


Figure 4. Violin plots of toxic metals (Pb, Hg, As) in food by region

Concentration in mg/kg, y-axis – logarithmic scale. AR – Ashanti Region, CR – Central Region, ER – Eastern Region, SR – Savannah Region, WNR – Western North Region, WR – Western Region.

3.4 Regression Analyses

To analyze if there is a correlation between food crop Hg and soil Hg, a regression was fitted to the data. Location-level soil Hg showed no clear association with food Hg. Compared with cereals (reference), fish had lower $\ln_{\text{food}}$ ($p < 0.001$), vegetables were modestly higher ($p=0.026$), and fruits, tubers, and rhizomes did not differ materially from cereals ($p=0.82$) (**Table 7**). The region random intercept captured residual between-region variability. **Figure 5** displays parallel fitted lines (no interaction) with 95% confidence ribbons for each food type across the observed range of centered $\ln(1+\text{soil Hg})$. Values reported under the reporting limit were set to the reporting limit. As for As, location-level soil As was positively associated with food As ($p < 0.001$), corresponding to roughly a 14% increase in $(1+\text{As})$ per 1-unit increase in $\ln(1+\text{soil As})$ (95% CI: +8% to +20%) (**Table 8**). Relative to cereals (reference), fish were much higher and vegetables were modestly higher in As. Fruits, tubers, and rhizomes did not differ materially from cereals (all $p \geq 0.49$). The figure shows parallel fitted lines (no interaction) with 95% ribbons for each food type across the observed range of centered $\ln(1+\text{soil As})$.

Table 7 Regression analysis for Hg

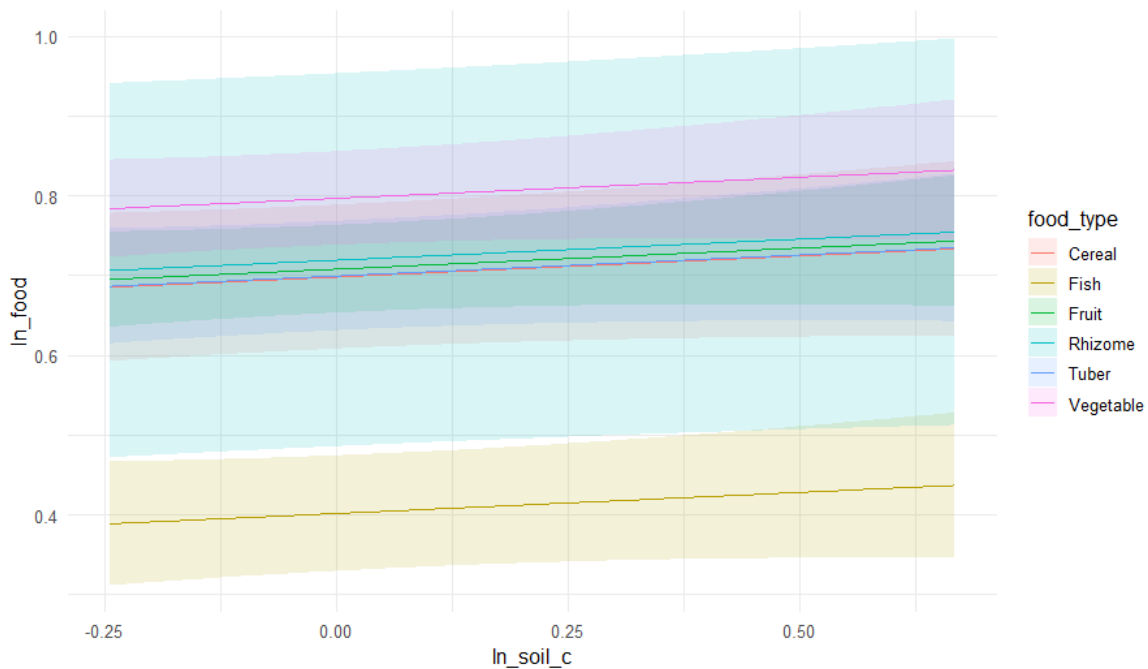
Term (reference=Cereal)	Estimate (β)	SE	95% CI	p-value
In_soil_c	0.0529	0.0469	[-0.039 - 0.1448]	0.261
Fish	-0.2966	0.0486	[-0.3919 - -0.2012]	<0.001
Fruit	0.0099	0.0424	[-0.0731 - 0.0929]	0.816
Rhizome	0.0211	0.1226	[-0.2192 - 0.2615]	0.863
Tuber	0.0014	0.0472	[-0.0911 - 0.0938]	0.977
Vegetable	0.0987	0.0437	[0.013 - 0.1844]	0.0256

Note: Estimates are on the $\ln(1+Hg)$ scale. Hg = mercury, Estimate (β) = Regression coefficient (Beta), SE = Standard Error, 95% CI = 95% Confidence Interval.

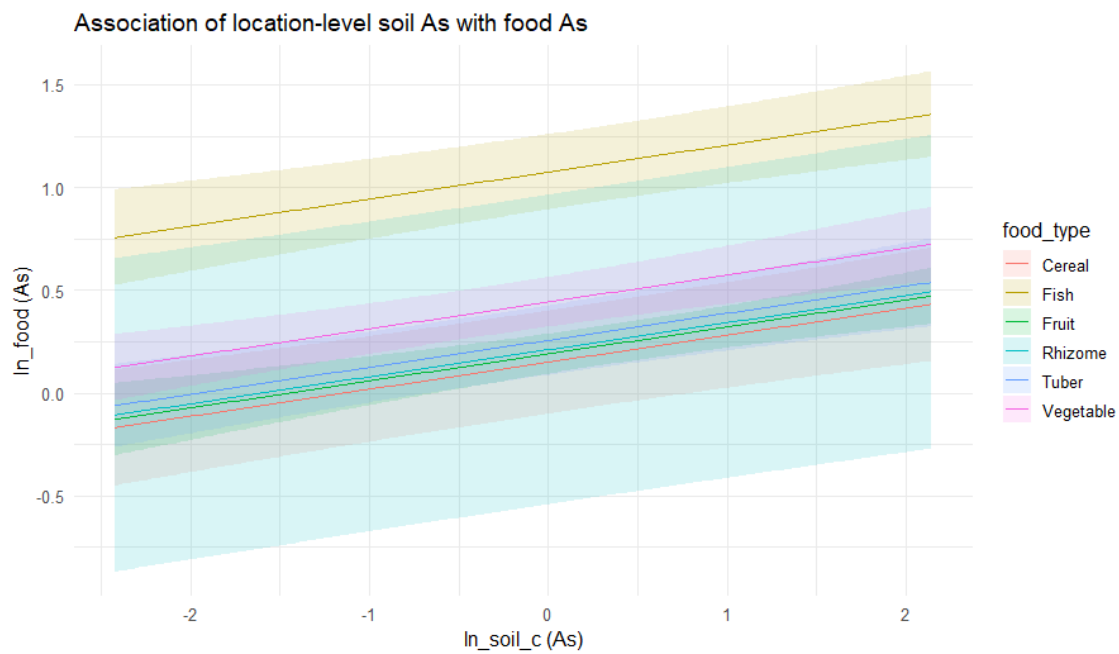
Table 8 Regression analysis for As

Term (reference=Cereal)	Estimate (β)	SE	95% CI	p-value
In_soil_c	0.1314	0.0274	[0.0777 - 0.1852]	<0.001
Fish	0.9255	0.1585	[0.6148 - 1.2361]	<0.001
Fruit	0.0406	0.1373	[-0.2285 - 0.3097]	0.768
Rhizome	0.061	0.4049	[-0.7326 - 0.8546]	0.88
Tuber	0.1069	0.1544	[-0.1958 - 0.4096]	0.49
Vegetable	0.293	0.1421	[0.0144 - 0.5716]	0.0411

Note: Estimates are on the $\ln(1+As)$ scale. As = arsenic, Estimate (β) = Regression coefficient (Beta), SE = Standard Error, 95% CI = 95% Confidence Interval.



a



b

Figure 5. Predicted values of mercury (a) and arsenic (b) by food type

Figure 5 shows the predicted values of $\ln(1+\text{food Hg})$ by centered $\ln(1+\text{soil Hg})$ from the GAM adjusting for food type, a region random intercept, and a 2-D spatial smooth ($n = 169$). Lines show marginal

predictions by food type; shaded bands are 95% CIs for parametric terms. The soil–food slope is positive but not statistically significant overall.

4. Discussion

4.1 Health Risks from Environmental Exposure

The results of this study indicate widespread contamination by toxic metals, particularly As, Pb, and Hg. Potential exposure pathways were identified and reflected by levels of toxic metals above threshold levels in soil, water, fish, and food crops across ASGM-impacted communities. This mixed exposure setting raises serious public health concerns.

As was detected in soil and some water samples above permissible limits. Exposure to elevated As through soil, water, and food has been associated with skin lesions, dermatoses, skin cancer, nervous system disorders, heart disease, gangrene, ischemic heart disease, and erectile dysfunction (Nordberg & Costa, 2021).

Children are especially vulnerable to Pb poisoning due to higher absorption rates and developing nervous systems. Pb was consistently elevated in sediment and water samples across study sites. Even low-level of Pb exposure impairs brain development in children, reducing intelligence, causing behavioral changes, and lowering educational attainment and lifetime earnings (Amitai et al., 2010; Lanphear et al., 2019; Nevin, 2007; Wright et al., 2008). Pregnant women with elevated blood Pb levels are at risk of adverse birth outcomes, as Pb crosses the placenta (Cantor et al., 2024; Flora et al., 2012). Pb exposure is also associated with stunting, anemia, kidney disorders, reproductive toxicity, immune suppression, gastrointestinal issues, and cardiovascular disease (Bellinger, 2008; Bergdahl & Skerfving, 2022).

Cd, found in fish and some water samples above permissible limits, poses risks of kidney damage, respiratory problems, and osteoporosis (Järup & Åkesson, 2009; Nordberg & Costa, 2021).

Hg, though not consistently above limits in this study, remains highly toxic and elevated levels were found in air at one site as well as multiple samples of soil, water, and food crops. Elemental, organic, and inorganic mercury are all highly toxic substances, each with different pathways of exposure and health effects, and all are present in ASGM settings (Bose-O'Reilly & Landrigan, 2021). Elemental Hg, often used in gold amalgamation, readily vaporizes during burning and is inhaled by miners, leading to neurological and renal damage (Bose-O'Reilly et al., 2017, Bose-O'Reilly & Landrigan, 2021). Organic Hg, such as methylmercury formed through environmental transformation, bioaccumulates in fish and poses a long-term dietary risk to surrounding communities (Ha et al., 2017). Methylmercury, mainly ingested via predatory fish, is a potent neurodevelopmental toxin during prenatal and postnatal stages (Fowler & Zalups, 2022; Ha et al., 2017) and is classified as a Group 2B carcinogen (Fowler & Zalups, 2022).

4.2 Governance and Equity

Regulatory gaps and ineffective environmental monitoring of ASGM operations in Ghana

The findings of this study reflect how weak governance and institutional fragmentation continue to exacerbate environmental and public health risks in Ghana's ASGM sector. Across multiple sites, Hg, As, and Pb concentrations in soil, water, fish, and vegetables far exceed national and WHO standards. The persistence of such contamination underscores long-standing gaps in enforcement and environmental monitoring.

A major precursor of informality in the sector is the cumbersome licensing process, compelling many miners to bypass the legal system and operate informally, outside the oversight of the Minerals Commission and the Ghana EPA (McQuilken & Hilson, 2016; Osei-Kojo & Andrews, 2016). The problem is compounded by poor institutional coordination. For instance, Ghana's Minerals and Mining Act of 2006 (Act 703) requires District Assemblies to be notified of ASGM licensing proceedings, yet their specific responsibilities, authority, and resources for ASGM governance are not clearly defined (Forkuor et al., 2020). A further regulatory gap is the lack of adequate consultation of stakeholders, particularly with small-scale miners, during policy design (McQuilken & Hilson, 2016; Osei-Kojo & Andrews, 2016).

Many small-scale miners lack adequate knowledge of existing mining laws, environmental regulations, and safe mining practices (McQuilken & Hilson, 2016).

4.3 Community Vulnerability and Patterns of Environmental Injustice

Demographic and occupational groups most vulnerable to toxic metal exposure in ASGM

ASGM communities are particularly vulnerable to toxic metal exposure. They often work in cramped, poorly ventilated environments with primitive equipment, which increases their risk of inhaling silica dust, Hg vapors, and poisonous gases such as methane, both underground and during milling and gold extraction processes (Bansah et al., 2016; Aram, 2021a; Yakovleva et al., 2022). The results of our study corroborate these risks: Hg vapor levels at Wassa Kayianko exceeded recommended limits, with smelting peaks as high as 150 µg/m³. The nonuse of personal protective equipment and conventional mining techniques heighten the dangers, resulting in occupational disorders such as silicosis and acute mercury poisoning (Burki, 2022; Singo et al., 2022). Women in ASGM, as observed in the Savannah region, frequently work in ore processing, including washing, grinding, and amalgamation with Hg, which can result in chronic exposure. Hg is detrimental to pregnant women because it passes through the placental barrier and impairs embryonic brain development (Aram, 2021b). Children in ASGM communities are often actively involved in mining activities and directly exposed to polluted air, water, food, and soil. Our findings that As and Pb levels in crops such as *kontomire* and pumpkin leaves exceeded FAO/WHO thresholds highlight potential serious risks to children, who are physiologically more susceptible to neurotoxic and developmental harm.

Additionally, consumers of food crops grown near ASGM sites are also under increased risk. In Ashanti and Western regions, food crops sampled (*kontomire*, tomato, pumpkin leaves) showed toxic metal concentrations high enough to pose chronic exposure risks for local populations. These findings corroborate evidence that toxic metals discharged into the environment via tailings, wastewater, and air emissions can remain in soils and bioaccumulate in food crops (Achina-Obeng & Aram, 2022). A considerable proportion of miners and community members are uninformed of the long-term health consequences of exposure (Bansah et al., 2016; Aram, 2021a), impeding both prevention and early detection. In Ghana, there are limited alternative sources of income that can compete with the instant cash rewards of ASGM (Hilson & Hu, 2022).

Livelihood diversification is therefore critical. Options include repurposing abandoned pits for aquaculture (FAO, 2023). However, previous initiatives such as Prestea's corporate-sponsored fish farming project failed due to poor water quality management and lack of technical follow-up, underscoring the need for sustained technical oversight (Adranyi et al., 2024).

4.4 Solutions and Policy

Mining laws, regulations, and policies

ASGM intersects with multiple regulatory institutions including the Ghana EPA, Minerals Commission, and local government authorities, requiring an integrated governance and formalization strategy across the value chain. Act 703 defines small-scale mining operations, sets out application and renewal procedures, and imposes operational and environmental conditions, including the need for EPA permits and, for larger operations, environmental impact assessments. Yet, the efficiency of its implementation and its consistency with policies in other mining-sensitive sectors (such as land use, forestry, and local development planning) remain uncertain.

Globally, ASGM contributes 20% of gold output, sustaining the livelihoods of 15–20 million people, largely driven by youth unemployment and rising gold prices (World Gold Council, 2022; Quijano Vallejos et al., 2020). Across Africa, an estimated 10 million mostly unlicensed artisanal miners extract gold, diamonds, and bauxite (World Bank, 2020). In Ghana, ASGM is a vital livelihood source for rural populations (Persaud et al., 2017). However, operations are often informal, with deprived communities relying on rudimentary tools and intensive manual labor (Boafo et al., 2019; Eshun & Okyere, 2017). In recent years, influential actors including politicians, expatriates, and mercenaries have expanded ASGM with heavy machinery and illegal land invasions, intensifying environmental degradation and food insecurity (Carvalho, 2017; Boadi et al., 2016).

Ghana's legislative and regulatory frameworks have historically favored large-scale over small-scale mining (McQuilken & Hilson, 2016). Reforms have often introduced inefficiencies or gaps (McQuilken & Hilson, 2016). The Provisional National Defense Council (PNDC) Law 218, established in 1986 and revised in

1989, sought to formalize ASGM, but illicit and harmful practices persist (Government of Ghana, 1989). Attempts to curb illegal mining have sometimes displaced local communities from income sources (Eduful et al., 2020). Despite legalization in 1989, ASGM still faces fiscal, institutional, and political challenges (Hilson et al., 2017; Hilson & Hu, 2022). With ASGM contributing over 35% of Ghana's gold output (Ghana EITI, 2021), concerns about its environmental and social impacts, including child labor and high school dropout rates (Azumah et al., 2021), remain urgent. Aligning ASGM policies with those in agriculture, environment, and health is critical to advancing sustainable outcomes (Nilsson et al., 2012).

Mining laws, regulations, and institutional arrangements

Ghana's mining sector is primarily overseen by the Ministry of Lands and Natural Resources (MLNR), the Minerals Commission, and the Ghana EPA. The Mining Commission is "responsible for the regulation and management of the utilization of mineral resources and the coordination of policies related to them" (*Minerals Commission Act, 1993, Act 450, p.3*). Sections 81–99 of Act 703 solely cover small-scale mining, including land acquisition and licensing processes, the structure and functions of district mining offices, miners' obligations, and mercury distribution and usage. Act 703 prevents anyone, regardless of land ownership or title, from searching, exploring, prospecting, or mining for minerals unless they have been given a mineral right. Only Ghanaian citizens can possess mineral rights and provide ASGM support services, whether as individuals or cooperatives (*Minerals Commission Act, 2006, Act 703*). The Ghana EPA is responsible for granting environmental permits to mining companies to sustainably mine. Ghana has the right institutions, rules, and laws set up to effectively regulate and monitor mining operations, promoting development while minimizing environmental degradation (Asumda, 2022). However, the mining sector continues to face various regulatory challenges, including the inability to oversee multiple regulations, insufficient human and institutional capacity, and a lack of coordination among regulatory agencies, and political interference in the permitting process (Asumda, 2022).

4.5 Study Limitations

The assessment of toxic metals in environmental and food matrices provides insight into contamination levels across Ghanaian mining regions. However, several key limitations affect interpretation.

Temporal variability was not fully addressed, as air Hg concentrations are highly time- and temperature-sensitive. Air sampling was limited to specific periods, and peak readings (e.g., 150.20 µg/m³ at Wassa Kayianko) may reflect localized smelting events rather than typical conditions.

Spatial heterogeneity also limits generalizability. Although over 1,000 soil samples were taken, anomalies such as extreme As readings in Konongo Zongo (10,060 ppm) may not represent regional averages. Sampling density varied between media, with far fewer water and crop samples (e.g., only 69 water samples overall), reducing robustness.

Speciation of Hg and As was not performed; only total concentrations were measured. Since toxicity depends on chemical species (e.g., methylmercury, inorganic arsenic), risk may be over- or underestimated. This limitation is especially relevant for crop and fish samples.

Other constraints include limited crop sample numbers, difficulty in obtaining fish samples due to seasonal variations and polluted waterbodies, absence of national food standards (necessitating reliance on WHO/FAO/EU benchmarks), and lack of bioavailability or exposure pathway analysis. Without these, results cannot fully reflect actual health risks in Ghanaian communities.

Future studies should integrate representative sampling, metal speciation, repeated temporal monitoring, and biomonitoring to provide a more reliable risk assessment.

5. Conclusions

In this study, trend analyses revealed significant regional differences in soil heavy metal contamination, with elevated levels of Hg, Pb, and As observed in several ASGM sites, particularly in the Ashanti and Western regions. Some soil samples far exceeded international and EPA thresholds, confirming serious localized risks and highlighting the need for targeted remediation strategies. By contrast, water, air, and food samples showed limited or inconsistent regional trends.

Food samples generally showed lower levels of Hg and Pb, though some elevated concentrations were recorded, particularly in vegetables from the Western Region. As levels were notably high, underscoring the need for further research, including speciation analysis.

XRF measurements showed strong and statistically significant correlations with laboratory ICP-MS results for key metals. While XRF measurements tended to underestimate Hg and Pb and overestimate As compared to laboratory values, the results confirm the XRF's reliability for rapid risk assessment and hotspot mapping.

This study demonstrates the need for urgent reforms that unite governance, community action, and sustainable alternatives in Ghana's ASGM sector. Further research, particularly human biomonitoring studies of multiple metals in vulnerable groups, such as pregnant women and children, is urgently needed to accurately assess health hazards. The study also highlights the need for targeted health interventions, including health surveillance, public education, and remediation of affected areas. The findings are expected to contribute significantly to national and regional efforts to mitigate environmental and health risks associated with ASGM. They will also support evidence-based policymaking, capacity building, and advocacy for sustainable practices within the ASGM communities and sector.

6. Declarations

All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

LIST OF ACRONYMS

AC	Ankobra Community
AK	Akwaboso
APHA	American Public Health Association
AR	Ashanti Region
As	Arsenic
AS	Asiakwa
ASGM	Artisanal and Small-scale Gold Mining
BMUV	(German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection)
Cd	Cadmium
CI	Confidence Interval
CR	Central Region
DA	Dakrupe
EC	European Commission
EPA	Environmental Protection Authority (Ghana)
ER	Eastern Region
EU	European Union
FAO	Food and Agriculture Organization
GA	Generalized Additive Model
GM	Geometric Mean
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
IDW	Inverse Distance Weighting
ISO	International Organization for Standardization
JT	Jonckheere Terpstra (trend test statistic)
KO	Konongo Odumase
KZ	Konongo Zongo
LA	Lake Amponsah
LMU	Ludwig-Maximilians Universität (Munich, Germany)
LOD	Limit of Detection
MAX	Maximum
MC	Minerals Commission (Ghana)
MEST	Ministry of Environment, Science and Technology (Ghana)
MIN	Minimum
MLNR	Ministry of Lands and Natural Resources (Ghana)
NY	Nyamebekyere
OS	Osino
Pb	Lead
PNDC	Provisional National Defense Council
Q-Q	Quantile-quantile (type of plot)
RL	Reporting Limit
SD	Standard Deviation
SR	Savannah Region
TA	Tinga

TSIP	Toxic Sites Identification Program
TVET	Technical and Vocational Education and Training
U.S. EPA	United States Environmental Protection Agency
WHO	World Health Organization
WK	Wassa Kayianko
WNR	Western North Region
WR	Western Region
XRF	X-ray Fluorescence

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