

POLLUTION INDICES AND HEALTH RISK DUE TO MERCURY IN THE BUHEMBA ARTISANAL AND SMALL-SCALE GOLD MINE OF TANZANIA

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ABSTRACT

This study assessed mercury (Hg) contamination and associated ecological risks in soils from the Buhemba artisanal and small-scale gold mining (ASGM) area in Tanzania. Soil samples ($n = 40$) were collected from depths of 0-20 cm and 20-40 cm and analyzed using Energy Dispersive X-Ray Fluorescence (ED-XRF) utilizing the XOPOS 4R0138 instrument. The findings revealed that the average total Hg levels in mining soil were 23.58 mg/kg at a depth of 0-20 cm and 7.30 mg/kg at 20-40 cm—exceeding national and international limits. The contamination/pollution factor and geo-accumulation index were 78.60 and 3.97 at 0-20 cm, and 24.33 and 2.28 at 20-40 cm. Additionally, the prospective ecological risk index and risk quotient were respectively 3143.73 and 589.45 at 0-20 cm, and 973.15 and 182.47 at 20-40 cm. Hg concentrations in Buhemba ASGM soils ranged (1.23–41.25 mg/kg). Pollution indices ($CF \geq 16$; $I\text{-geo } 3\text{--}4$; $ER \geq 320$; $RI \geq 600$; $RQ \geq 1$) confirmed severe Hg contamination. The significant difference of ($p < 0.05$) was revealed between soil depths and a positive relationship between Hg level and risk indices. These results suggest that ASGM activities are the primary source of pollution. On the other hand, analytical limitations and the use of international background values may lead to uncertainties. This work highlights considerable potential human health and ecological risks, underscoring the need for remediation plans and reinforced environmental management. Carrying out Hg remediation plans and soil improvement technologies are immediately needed. Community-based interventions and strengthened regulatory oversight are also recommended.

Keywords: Mercury, Heavy metals, health risks, indices, pollution.

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INTRODUCTION

Mercury is a heavy metal that contaminates the environment, making it a serious threat to ecosystems (Gibb & O'Leary, 2014; Rice *et al.*, 2014). It mainly comes from gold mining activities when amalgamation processes are used, which contaminates the environment with mercury, especially in small-scale mining enterprises known as artisanal small-scale gold mining (ASGM). ASGM is considered the most significant anthropogenic source of mercury pollution, particularly in developing countries because of weak regulatory frameworks. In Tanzania (Mariki *et al.*, 2024) and East Africa region (Raoilimanantsoa *et al.*, 2026; Ssenku *et al.*, 2023), mercury is extensively used in gold extraction processes, which leads to heavy pollution of the environment with this toxic metal. When mercury is released into the environment, it ends up in the soil and ecosystems, posing environmental health risks (Dong & Li, 2024).

In the soil, mercury is strongly bound to organic matter and fine particles (Schwartz *et al.*, 2019). Mercury binds strongly to organic matter and fine particles, which causes it to accumulate in the topsoil layer. Nonetheless, this does not eliminate the risk of it penetrating deeper into the soil profile under specific environmental conditions. The processes by which mercury is emitted into the atmosphere, accumulates, transforms, and is discharged to the earth's surface can be better understood by looking at them in conjunction with (i) emission sources, (ii) accumulation and transformation processes in the soil, (iii) contamination assessment using pollution indices, and (iv) the environmental and health effects. Understanding the amount of mercury contamination in the soil is critical because it helps determine the causes of pollution (Eckley *et al.*, 2020). Various analytical methods, such as Atomic Absorption Spectroscopy (AAS), Atomic Fluorescence

Spectroscopy (AFS), Energy Dispersive X-rays Fluorescence (ED-XRF) and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS)-based techniques are available for monitoring mercury levels, depending on technological capacity. The ED-XRF in particular, is highly sensitive and effective for detecting mercury in soil samples (Almeida *et al.*, 2016).

Since soil acts as a natural sorbent for contaminants, including mercury, it is essential to analyze its biological and ecological impacts. Studying geo-accumulation and ecological risk assessments can help determine the overall contamination level. Multiple indices such as the contamination/pollution factor (EF) and the geo-accumulation index (I-geo) (Maulana *et al.*, 2023) are used to ensure consistent findings. Additionally, determining the CF index and toxicity response (Tr) values is essential for evaluating ecological risks from anthropogenic mercury contamination (Maulana *et al.*, 2023).

To effectively manage mercury contamination, soil quality guidelines (SQG) should be followed alongside appropriate remediation technologies. International and national threshold limits for mercury concentrations in soil range from 0.05 mg/kg to 1 mg/kg and 2 mg/kg (Maulana *et al.*, 2023; Sanga *et al.*, 2023), respectively. If mercury levels exceed these limits, health and ecological hazards must be evaluated, and remediation measures should be implemented as part of the SQG framework (Randall & Chattopadhyay, 2013). Recent studies have explored various evaluation techniques for mercury-contaminated soil (Keane *et al.*, 2023; Liu *et al.*, 2018). However, the long-term effectiveness of these techniques in evaluating levels and ecological risks in real-world contamination sites remains uncertain.

Focus

Therefore, this study aims to evaluate and analyze mercury contamination, pollution levels, and environmental risks in soils of a Tanzanian area affected by ASGM using multiple contamination and risk assessment indices (EF, I-geo, CF, Tr, RQ, RI). These findings will contribute to future mercury management and remediation efforts.

MATERIALS AND METHODS (METHODOLOGY)

Study area

This study was carried out in Buhemba ASGM (Figure 1), a tropical Savanna, wet area of Tanzania. The research area is situated at an elevation of 1409 meters above sea level, with an average annual rainfall of 600 mm and a mean temperature of 23.95°C. The study covered part of the milling and washing sub-areas within a mining site, selected based on the activities carried out there. In these sub-areas, the activities of crushing ores are done. Also, the crushed materials are locally washed to liberate gold. In the stage of washing, workers use pure mercury for gold recovery.

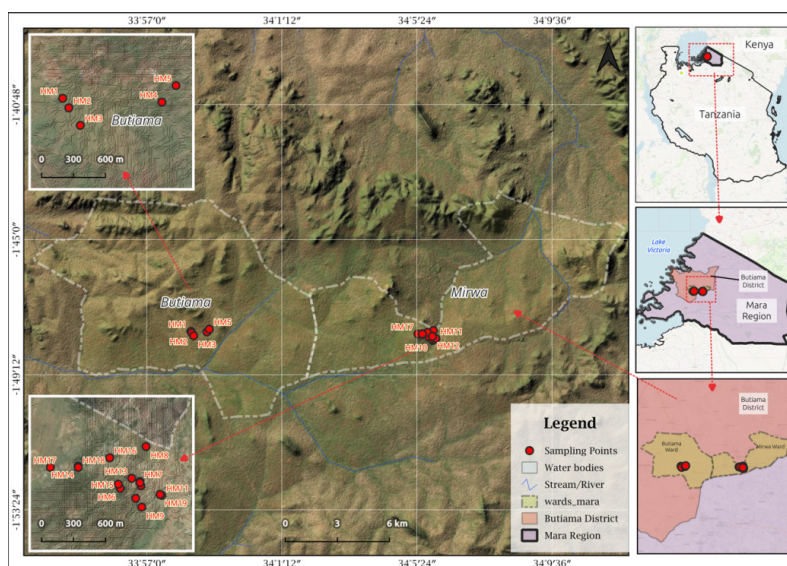


Figure 1: A map of Tanzania (top right) showing the Mara region, Butiama district (middle right), the study area (bottom right), and sampling points (left).

Soil Sampling

Soil samples were taken from washing and milling areas which represent the primary points of Hg use and release in the ASGM. In order to improve representativeness and minimize local heterogeneity, three to five sub-samples were collected and composited. Soil samples (N=40) were collected at depths of 0-20 cm (20 samples) and 20-40 cm (20 samples). The depth intervals were

selected based on standard environmental assessment practices to evaluate both surface contamination and potential migration of Hg. Sampling mercury-contaminated soil at depths of 0–20 cm and 20–40 cm is a standard practice in environmental assessments to understand the distribution and mobility of mercury (Hg) within the soil profile (Eckley *et al.*, 2020).

The sampling size and distribution were designed to ensure adequate spatial representation of contamination across active mining areas.

Soil Analysis

Soil samples were oven-dried at 50 °C for 24 h to remove moisture and achieve a constant mass. The material was then grounded into a fine powder with a thoroughly cleaned mortar and pestle, and then sieved through a 2 mm stainless-steel sieve. 4 g of the sieved soil was mixed with 0.9 g of starch binder (Focus et al., 2021). The starch binder used in sample preparation was investigated and confirmed not to interfere with the determination of mercury (Miller et al., 2013). It was homogenized for 10 min in a pulverizer before it was pressed into 32 mm diameter pellets using a die pellet press (Focus et al., 2021). Mercury contents in soil samples were quantified using Energy Dispersive X-Ray Fluorescence (ED-XRF) spectroscopy, using XOPOS 4R0138 (Kleve, Germany). The instrument was calibrated beforehand, and a certified reference material (CRM) Montana Soil 2711a from National Institute of Standards and Technology (NIST) was analyzed under the same conditions to evaluate the procedure's accuracy.

Limit of detection (LOD) was determined by instrument specifications. Precision was evaluated by triplicate measurements with relative standard deviations below 5%. Measurement uncertainty was minimized by the calibration process. Quality control measures were taken, and statistical calculations were performed using Origin software.

Evaluation of Hg Contamination and Pollution Accumulation and Risk in Soil

This study adopted a soil quality threshold of 0.3 mg/kg for Hg, as established elsewhere (Sun et al., 2019). However, this value exceeds the safety limits set for soils by various organizations, including the WHO at 0.05 mg/kg and the European Union at 0.08 mg/kg (Tóth et al., 2016). Additionally, the study incorporated contamination and pollution factor indices, as well as ecological risk assessments, which are detailed in Tables 1, 2, and 3.

Index of Contamination/ Pollution Factor

The contamination/pollution factor (CF) and the geo-accumulation index (I-geo) were determined using equations 1 and 2, respectively (Nweke & Ukpai, 2016).

$$CF = \frac{ci}{c} \quad \text{eqn 1}$$

Where: C_i = Hg in the soil sample; C = Hg concentration within acceptable environmental limits (0.3 mg/kg). The Contamination Factor for Hg is a direct ratio that indicates the level of human-induced Hg enrichment in soil. Most uncontaminated soils have $CF < 1$, while values above that indicate increasing contamination depending on the magnitude (Table 1).

$$I - geo = \log_2 \left[\frac{ci}{1.5 \times Bn} \right] \quad \text{eqn 2}$$

Focus

Where: C_i = Hg in the soil sample; B_n = the geochemical background value for Hg in the soil (0.05 mg/kg (Pérez-Sirvent *et al.*, 2009)). The B_n for Hg is a global background level in soil that varies by region due to differences in geology, soil composition, and human activities. 1.5 is a background matrix correction factor.

Index of Ecological Risk

The ecological risk (ER) potential of Hg in soil was evaluated using contamination factor index values and pollutant toxicity (Tr) (Equation 3). Additionally, the risk index (RI) was used to quantify the ecological hazard posed by Hg in the soil (Equation 4). To estimate the potential risk of Hg contamination in the ecosystem, the risk quotient (RQ) index was calculated by dividing the Hg concentration by the predicted no-effect concentration (PNEC) of Hg (0.04 mg/kg) (Equation 5) (Mortazavi, 2018; Ripanda *et al.*, 2021; Zhang *et al.*, 2017).

$$ER = Tr \times CF$$

eqn 3

$$RI = \sum ER$$

eqn 4

$$RQ = \frac{C_i}{PNEC}$$

eqn 5

Where: CF= contamination/ pollution factor in the soil sample, and Tr represents the toxic reaction factor (Tr for Hg = 40 (Bjørklund *et al.*, 2017)) and C_i = Concentration of Hg in the soil sample. The pollution level of an area depends on various factors. Also, the status of a polluted environment varies according to the extent of pollution. The levels of the contamination factor classifying the potential health and ecological impacts are presented in Table 1. Moreover, the Geo-accumulation Index levels are categorized in Table 2. Table 3 further shows sequential pollution levels suggested by the Ecological risk factor.

Table 1: Criteria of CF Index

Symbol	Index Value	Criteria and Status
CF	1.1 – 2.0	Slightly polluted
	2.0 – 4.0	Pretty polluted
	4.1 – 8.0	Heavily polluted
	8.1 – 16	Very polluted
	≥16	Extremely polluted

Table 2: Criteria of RI and RQ

Index Value		Criteria
RQ	≤ 1	Low
	≥ 1	High
RI	≤ 150	Low
	150 – 600	Moderate
	300 – 600	Considerable
	≥ 600	High

Table 3: Criteria for the I-geo and ER Index

I-geo		ER	
Index value	Criteria	Index value	Criteria
≤ 0	Uncontaminated	≤ 40	Low
0 – 1	Uncontaminated to medium	40 - 80	Moderate
1 – 2	Medium contaminated	80 - 160	Considerable
2 – 3	Medium to highly contaminated	160 - 320	High
3 – 4	Highly contaminated	≥ 320	Very high
4 – 5	Highly to extremely contaminated		
≥ 5	Extremely contaminated		

Statistical Analysis

Descriptive statistics were supplemented with inferential statistical analyses to evaluate differences and relationships in mercury concentrations and associated indices. An independent sample t-test was applied to determine whether significant differences exist between surface (0–20 cm) and subsurface (20–40 cm) soil layers. Additionally, Pearson correlation analysis was performed to assess the relationships between mercury concentration and contamination indices (CF, I-geo, ER, RI, and RQ). Statistical significance was evaluated at $p < 0.05$.

Study Limitations

This work recognizes some limitations. First, local background/control soil samples were not collected due to logistical restrictions; therefore, global reference values were used

in computing pollution indices. This may introduce some uncertainty in estimating site-specific contamination levels. Second, even if ED-XRF offers reliable multi-element analysis, its detection limits and sensitivity may be lower compared to advanced techniques such as ICP-MS. These limitations have been considered in the interpretation of results.

RESULTS AND DISCUSSION

Table 4 shows the average levels of mercury for the samples of the study area. It is clearly noted that the average levels of mercury are above the recommended values by the national and international organizations (Liu et al., 2021; Taylor et al., 2005). The elevated Hg levels might be primarily attributed to artisanal and small-scale gold mining (ASGM).

Focus

In the study area, the mining activities especially the milling and washing activities are conducted anyhow without following environmental, health guidelines and

precautions (Semenkov & Koroleva, 2019; Tan, 2009),. The index values for each sampling point are presented in Table 4.

Table 4: Results of the total mercury and selected indices to soil samples of the Buhemba ASGM

Samples taken at the depth of 0-20 cm						Samples taken at the depth of 20-40 cm					
Code	Total Hg (mg/kg)	CF	I-geo	ER and RI	RQ	Code	Total Hg (mg/kg)	CF	I-geo	ER and RI	RQ
H1	7.42	24.73	2.31	989.33	185.50	HM1	1.23	4.10	-0.29	164.00	30.75
H2	6.11	20.37	2.03	814.67	152.75	HM2	2.31	7.70	0.62	308.00	57.75
H3	9.56	31.87	2.67	1274.67	239.00	HM3	1.34	4.47	-0.17	178.67	33.50
H4	4.85	16.17	1.69	646.67	121.25	HM4	9.32	31.07	2.63	1242.67	233.00
H5	16.91	56.37	3.49	2254.67	422.75	HM5	12.51	41.70	3.06	1668.00	312.75
H6	22.96	76.53	3.94	3061.33	574.00	HM6	4.61	15.37	1.62	614.67	115.25
H7	30.21	100.70	4.33	4028.00	755.25	HM7	1.90	6.33	0.34	253.33	47.50
H8	26.30	87.67	4.13	3506.67	657.50	HM8	6.98	23.27	2.22	930.67	174.50
H9	40.80	136.00	4.77	5440.00	1020.00	HM9	2.12	7.07	0.50	282.67	53.00
H10	39.02	130.07	4.70	5202.67	975.50	HM10	4.71	15.70	1.65	628.00	117.75
H11	36.71	122.37	4.61	4894.67	917.75	HM11	12.22	40.74	3.03	1629.73	305.58
H12	28.10	93.67	4.23	3746.67	702.50	HM12	10.21	34.03	2.77	1361.33	255.25
H13	13.40	44.67	3.16	1786.67	335.00	HM13	9.43	31.43	2.65	1257.33	235.75
H14	37.12	123.73	4.63	4949.33	928.00	HM14	11.32	37.73	2.92	1509.33	283.00
H15	41.25	137.50	4.78	5500.00	1031.25	HM15	9.98	33.27	2.73	1330.67	249.50
H16	26.23	87.43	4.13	3497.33	655.75	HM16	13.53	45.10	3.17	1804.00	338.25
H17	19.82	66.07	3.72	2642.67	495.50	HM17	15.70	52.33	3.39	2093.33	392.50
H18	39.62	132.07	4.72	5282.67	990.50	HM18	9.54	31.80	2.67	1272.00	238.50
H19	19.50	65.00	3.70	2600.00	487.50	HM19	2.34	7.80	0.64	312.00	58.50
H20	5.67	18.90	1.92	756.00	141.75	HM20	4.67	15.57	1.64	622.67	116.75

The assessment of mercury (Hg) contamination in surface (0–20 cm) and subsurface (20–40 cm) soil layers reveals a significant vertical and spatial variability in both the concentration and ecological risk indices across sampling locations.

The total Hg concentrations in surface samples (H1–H20) ranged from 4.85 to 41.25 mg/kg. Samples H9, H10, H15, and H18 contained high Hg levels (>35 mg/kg). These values are significantly higher than the normal background levels for uncontaminated soils (<0.1 mg/kg) (Gyamfi et al., 2021; Mantey et al., 2020), suggesting anthropogenic

contributions, possibly from mining activities. However, the concentrations for subsurface samples (HM1–HM20) were lower (1.23–15.70 mg/kg), indicating limited downward movement of mercury with depth. This observation can be attributed to mercury's strong adsorption capacity on organic matter and fine particles within the topsoil layer.

Contamination factors (CF) support these findings, with surface index values (16.17–137.50) indicating many sites fall within “Slightly to Extremely polluted categories” (Table 1).

While CF values for subsurface (20–40 cm) were generally lower (4.10–52.33), specific locations (e.g., HM17 and HM16) still exhibited signs of moderate to high contamination. The I-geo index values in surface soils ranged from 1.69 to 4.78, signifying contamination levels from moderately polluted (I-geo >1) to extremely polluted (I-geo >4) (Table 3). These values emphasize the significance of Hg enrichment and its ecological implications over the long term (Ogunyemi, 2023). The values of I-geo for the subsurface ranged from -0.29 to 3.39, with negative or near-zero readings in selected points (e.g., HM1, HM3), suggesting minimal anthropogenic activity or background levels. Ecological Risk (ER) and the derived Risk Index (RI) exhibited concerning trends. RI for the surface (0–20 cm) values ranged from 646.67 to 5500, with over half exceeding the threshold of 600, implying very high ecological risk. These risks are highly correlated with higher mercury concentrations in the topsoil (Esdaile & Chalker, 2018). In comparison, subsurface samples (20–40 cm) displayed lower RI values (164 to 2093.33), yet some sites (e.g., HM17 and HM16) approached the high-risk thresholds. Similarly, Risk Quotient (RQ) values followed this pattern, with surface soils reaching a maximum of 1031.25 (H15), while subsurface maximums reached 392.50 (HM17). These values indicate the potential for biological and ecological harm, particularly with prolonged exposure to surface soils (Gyamfi et al., 2021).

The elevated levels of mercury and the associated indices in surface soils suggest localized pollution, potentially from human activities (Obrist et al., 2018). The comparatively lower subsurface levels may imply limited leaching, which could be influenced by soil composition, pH, organic content, and moisture retention. However, the presence of elevated Hg in some deeper layers indicates mercury’s capacity to move vertically through disturbed or sandy soils.

Overall, the study highlights the necessity for environmental management, remediation strategies, and policy intervention in the study area. Regular monitoring, coupled with source identification, is vital to mitigate the long-term ecological and human health risks posed by mercury contamination.

Table 5 presents a comprehensive summary of the descriptive statistics generated in this study, offering an insight into the distribution, variability, and central tendencies of the key environmental contamination indicators. Specifically, the table reports the calculated values for the Contamination Factor (CF), Geo-accumulation Index (I-geo), Ecological Risk (ER), Risk Index (RI), and Risk Quotient (RQ). These indices provide quantitative insights into the extent of metal contamination, the degree of anthropogenic influence, and the potential ecological and human health risks associated with the given environmental matrices.

The statistical patterns reflected in these indicators serve as a basis for interpreting contamination severity, comparing risk levels across sampling sites, and identifying pertinent areas for mitigation or further investigation.

Table 5: Descriptive Statistics of the Index of CF, I-geo, and ER, RI, and RQ on the Buhemba ASGM Soil Contaminated with Hg.

Analysis/Index	N	Minimum	Maximum	Mean	Observation/Comment (s)
For samples taken at the depth: 0 to 20 cm					
Total Average Hg		4.85	41.25	23.58	Needs immediate actions
CF	20	16.17	137.50	78.60	Extremely polluted
I-geo		1.70	4.78	3.97	Very high contaminated
ER and RI		646.67	5500	3143.73	Very high contaminated
RQ		121.25	1031.25	589.45	Very high contaminated
For samples taken at the depth: 20 to 40 cm					
Total Average Hg		1.23	15.70	7.30	Remediation needed
CF	20	4.10	52.33	24.33	Above the average
I-geo		-0.29	3.39	2.28	Mean above the average
ER and RI		164.00	2093.33	973.15	Highly contaminated
RQ		30.75	392.50	182.47	Highly contaminated

The results presented in Table 5 reveal a concerning level of mercury (Hg) contamination in soil samples at both 0–20 cm and 20–40 cm depths, with stronger pollution indicators observed in the topsoil layer (0–20 cm).

The mean total mercury (Hg) concentration at 0–20 cm was 23.58 mg/kg with a range of (4.85 - 41.25 mg/kg). These values are significantly higher than the threshold level, indicating anthropogenic inputs. Different contamination indices including Enrichment Factor (EF), Geo-accumulation Index (I-geo), Ecological Risk (ER), Risk Index (RI), and Risk Quotient (RQ) agree the severe contamination of the soil with mercury. The mean Enrichment Factor (EF) was 78.60, signifying extreme enrichment, suggesting that anthropogenic activities contributed significantly to the pollution load in the study area (Mukherjee *et al.*, 2004). The mean I-geo value was 3.97, indicating that the soils were heavily to extremely polluted.

In addition, the ecological risk parameters, ER, RI (mean = 3143.73), and RQ (mean = 589.45) imply very high ecological risk. The mean RI, in particular, is particularly high, which suggests a significant threat to the ecosystem due to mercury pollution (Malehase *et al.*, 2017). Although, the contamination load was significantly lower in the subsurface, it is still considerably high to deserve urgent

environmental interventions. For instance, the mean Hg concentration at 20–40 cm was 7.30 mg/kg with a range of 1.23 to 15.70 mg/kg. Thus, contamination factors (CF) and I-geo indicate moderately to highly contaminated soils with average values of 24.33 and 2.28, respectively. These values suggest that the subsurface soils experienced considerable contamination that could have transpired vertically from the surface. Moreover, the mean ER and RI values (973.15) and RQ (182.47) indicate highly contaminated subsurface soils with elevated risk quotients.

The high risk quotient values at depths may pose a significant threat to ground water and water bodies hence causing adverse effects to the ecosystem (Ritter, 2002). The significant difference between the contamination indices between the surface and the subsurface soils suggests that anthropogenic activities at the surface have caused significant environmental pollution that could threaten groundwater systems.

The observed reduction in mercury concentration with depth suggests that there is minimal vertical migration under the existing environmental conditions. Nevertheless, different physiochemical processes and properties of the subsurface soils including texture, structure, redox potential, and humus content can significantly influence the mobility and hence the bioavailability of the metal.

The high mercury concentration at the surface is ecologically very significant because it is the layer where most biological activities take place. Thus, the high risk quotient values for both soil depths pose a significant threat to the immediate ecosystem, particularly invertebrates and plant roots.

An independent samples t-test was performed for real values to compare mercury (Hg) concentrations between surface (0-20 cm) and subsurface (20-40 cm) soils. The results indicated that there was a significant difference between the mercury concentrations in the two depths ($t = 5.32$, $p < 0.001$). This implies that mercury concentrations in surface soils were significantly higher than those in the subsurface soils. In other words, the artisanal

mining activities have caused extremely high pollution in the surface soils compared to subsurface soils. The independent samples t-test results show that the artisanal small-scale gold mining activities contribute significantly to the surface soil contamination by mercury.

Figure 2 shows the distribution of mercury concentrations for the surface (0-20) and subsurface (20-40) soil samples using boxplots. According to the figure, surface soils generally had higher mercury concentrations than the subsurface soils as indicated by the medians. The figure also shows that mercury concentrations were more variable in the surface soils than in the subsurface soils as demonstrated by the interquartile ranges and the presence of outliers. The high variability in mercury concentrations can be attributed to the direct anthropogenic inputs to the surface soils. Compared to the surface, subsurface soils had lower mercury concentrations and variability in the distribution. It can be concluded from the figure that mercury contamination was generally higher in the surface horizon than in the deeper horizon.

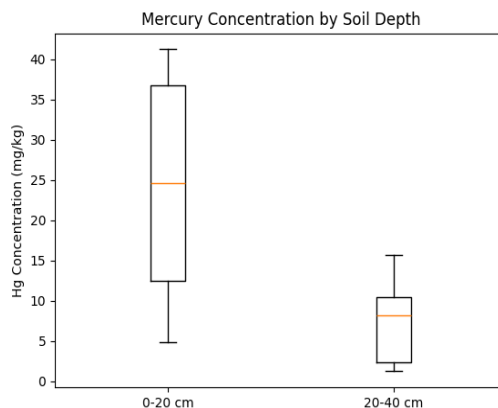


Figure 2: Boxplot showing the distribution of mercury concentrations in surface (0–20 cm) and subsurface (20–40 cm) soils. The plot indicates significantly higher concentrations and variability in surface soils.

Focus

The mean mercury concentrations in the 0-20 cm and 20-40 cm soil horizons are compared in Figure 3. It can be seen that the content in the 0-20 cm layer was higher compared to the subsurface layer. This suggests that most of the mercury was accumulated in the topsoil, which might be related to the direct impact of mining activity on the horizons present above the ground.

The fact that the second layer contains significantly less mercury demonstrates the insignificance of mechanical disturbance and penetration of the metal beneath the surface. Thus, Figure 3 clearly shows the degree of accumulation and contamination of soils with mercury.

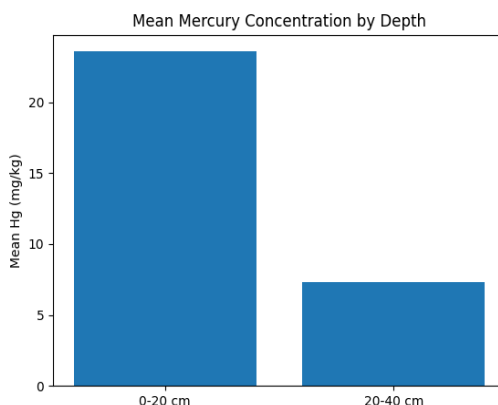


Figure 3: Mean mercury concentrations in surface (0–20 cm) and subsurface (20–40 cm) soils, illustrating higher contamination levels in the topsoil layer.

Pearson correlation analysis revealed perfect positive correlations ($r = 1.00$) between mercury (Hg) concentrations and all derived indices (CF, ER, RI, and RQ) (Table 6). This result is expected since these indices are constructed mathematically based on Hg concentrations. Thus, the strong correlations confirm that,

increases in Hg concentration lead to proportional increases in contamination and ecological risk indices and directly affect ecological risk levels. The strong relationships validate the use of these indices as reliable indicators of mercury contamination and environmental risk in the study area

Table 6: Pearson Correlation Matrix (Surface Soil Data) between Hg Concentration and Contamination Indices

Variable	Hg	CF	ER	RI	RQ
Hg	1.00	1.00	1.00	1.00	1.00
CF	1.00	1.00	1.00	1.00	1.00
ER	1.00	1.00	1.00	1.00	1.00
RI	1.00	1.00	1.00	1.00	1.00
RQ	1.00	1.00	1.00	1.00	1.00

Due to the inherent mathematical dependency between Hg concentration and the calculated indices, correlation analysis mainly serves as a validation tool rather than an independent statistical inference.

The spatial distribution pattern of mercury (Hg) concentrations in the surveyed soil profile depths of 0–20 and 20–40 cm was depicted in Figure 4. Overall, the concentrations of Hg were found to be higher in the topsoil (0–20 cm) than in the subsoil (20–40 cm) at almost all sampling points. Several hotspots of mercury contamination were identified in the topsoil at H9, H10, H14, H15, and H18, with more than 35 mg/kg (Figure 4). The

observed spatial distribution of Hg can be primarily explained by anthropogenic point sources such as gold mining activities at the sites, which release this heavy metal into the environment through amalgamation and ore washing processes. On the other hand, the decrease in Hg concentrations with depth implies that this element tends to adhere to the soil particles and does not move deeper into the ground.

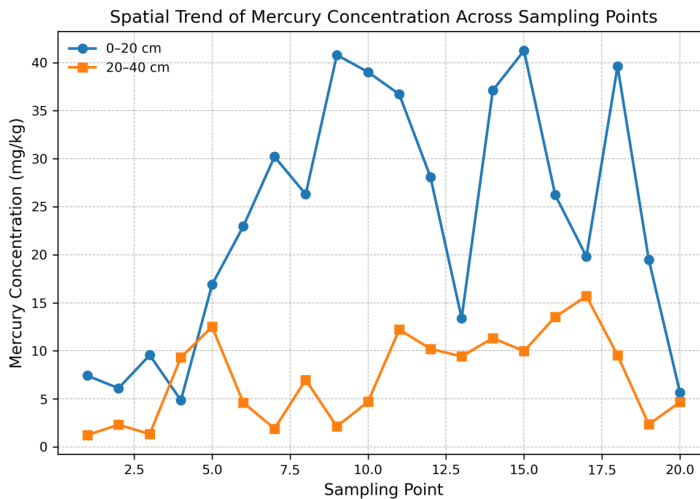


Figure 4: Spatial trend of mercury concentration across sampling points for surface (0–20 cm) and subsurface (20–40 cm) soils.

Figure 5 presents a heat map created using the mercury concentrations at sample points for the two depths. As seen from the figure, the highest mercury concentrations were detected in the topsoil (0–20 cm). Nevertheless, there was also an occurrence of high Hg levels in the deeper layer (20–40 cm). Thus, it can be concluded that there are local areas of Hg contamination both on the surface and at a certain depth below the surface. The heat

map visually presents the pattern of mercury pollution in the study area and allows us to identify local contamination “hotspots.” Consequently, targeted action must be taken to remediate contaminated sites, and particular attention should be paid to areas with high concentrations of mercury. This research highlights the significance of such activities in heavily polluted abandoned ASGM areas.

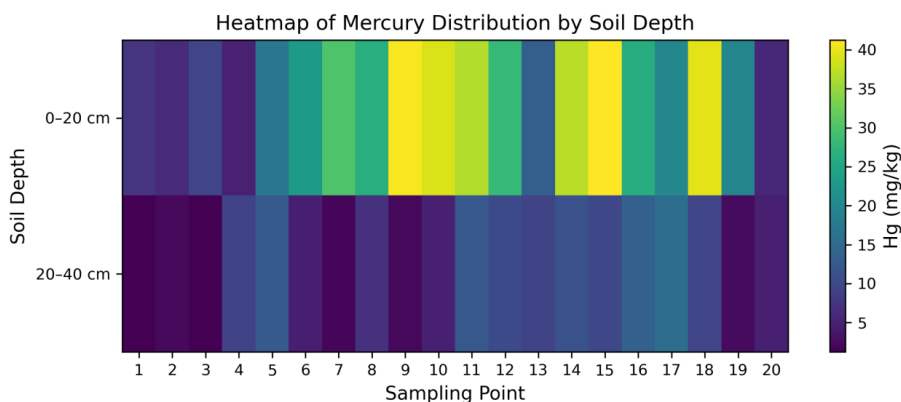


Figure 5: Heatmap showing the spatial distribution of mercury concentrations across sampling points and soil depths.

Potential exposure routes for humans in the study area were identified as ingestion of contaminated soil particles, inhalation of mercury-laden dust, and dermal contact during mining and agricultural activities. In addition, mercury may enter the food chain through plant uptake which poses a long-term health risk to the local communities. Although a quantitative health risk assessment was not the scope of the study, such a high concentration of mercury indicates a significant potential for human exposure.

Given the extremely high level of contamination, remediation measures to lower the concentration of mercury in the ground should be implemented. Some possible remediation measures to consider are phytoremediation, soil washing, and stabilization using chemical amendments or sulfur-based compounds. Further, it is recommended to conduct a comprehensive risk assessment while considering the bioavailability, speciation of Hg, and exposure pathways in order to optimize the management strategies.

Further, long-term monitoring should be carried out to ensure that the contamination is not spreading and the implemented management measures are taking effect. It is

also recommended to conduct a study on the contamination sources in order to identify the main contributors to the pollution and take appropriate actions.

CONCLUSION

The study found that significantly high levels of mercury (Hg) were present in the surveyed area reaching up to 1.23-41.25 mg/kg which far exceeds the globally recommended limit (Fernandes et al., 2021).

The study established serious levels of soil contamination on all types of soil with respect to contamination and ecological risk indices (CF, I-geo, ER, RI, and RQ) which indicate high ecological risks and potential for pollution. The study concluded that ASGM activities are the primary contributor to mercury pollution. The high concentrations of Hg pose a significant risk to the local ecosystem and human health through various exposure routes (Ha et al., 2017; Kao et al., 2004). However, this study utilized global background values instead of local background values due to the lack of control samples. Additionally, some systematic errors may arise because of the limitation of the ED-XRF method.

Practically the study provides key insights into mercury pollution in artisanal and small-scale mining areas. Therefore, the need for the implementation of management strategies such as soil stabilization and phytoremediation and strengthening of regulations and community-based risk management to reduce the impact of heavy metals especially mercury on human health and the environment was emphasized. Long-term monitoring programs and further studies to assess the impact of mercury on human health should be considered in future studies.

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CONFLICT OF INTEREST

The author declares no conflict of interest exists.

AUTHOR CONTRIBUTION

Dr. Erasto Focus did all the works regarding this manuscript.

REFERENCES

Almeida, I. L., Oliveira, M. D., Silva, J. B., & Coelho, N. M. (2016). Suitable extraction of soils and sediments for mercury species and determination combined with the cold vapor generation atomic absorption spectrometry technique. *Microchemical Journal*, 124, 326-330.

Bjørklund, G., Dadar, M., Mutter, J., & Aaseth, J. (2017). The toxicology of mercury: Current research and emerging trends. *Environmental research*, 159, 545-554.

Dong, T., & Li, H. (2024). Neurological risks arising from the bioaccumulation of heavy metal contaminants: A focus on mercury. *Environmental Toxicology*, 39(5), 2692-2705.

Eckley, C. S., Gilmour, C. C., Janssen, S., Luxton, T. P., Randall, P. M., Whalin, L., & Austin, C. (2020). The assessment and remediation of mercury contaminated sites: A review of current approaches. *Science of the Total Environment*, 707, 136031.

Esdaile, L. J., & Chalker, J. M. (2018). The mercury problem in artisanal and small-scale gold mining. *Chemistry—A European Journal*, 24(27), 6905-6916.

Fernandes, I. O., Gomes, L. F., Monteiro, L. C., Dórea, J. G., & Bernardi, J. V. E. (2021). A scientometric analysis of research on world mercury (Hg) in soil (1991–2020). *Water, Air, & Soil Pollution*, 232(7), 254.

Focus, E., Rwiza, M. J., Mohammed, N. K., & Banzi, F. P. (2021). Health risk assessment of trace elements in soil for people living and working in a mining area. *Journal of environmental and public health*, 2021(1), 9976048.

Gibb, H., & O’Leary, K. G. (2014). Mercury exposure and health impacts among individuals in the artisanal and small-scale gold mining community: a comprehensive review. *Environmental health perspectives*, 122(7), 667-672.

Gyamfi, O., Sørensen, P. B., Darko, G., Ansah, E., Vorkamp, K., & Bak, J. L. (2021). Contamination, exposure and risk assessment of mercury in the soils of an artisanal gold mining community in Ghana. *Chemosphere*, 267, 128910.

Focus

- Ha, E., Basu, N., Bose-O'Reilly, S., Dórea, J. G., McSorley, E., Sakamoto, M., & Chan, H. M. (2017). Current progress on understanding the impact of mercury on human health. *Environmental research*, 152, 419-433.
- Kao, R. T., Dault, S., & Pichay, T. (2004). Understanding the mercury reduction issue: the impact of mercury on the environment and human health. *Journal of the California Dental Association*, 32(7), 574-579.
- Keane, S., Bernaudat, L., Davis, K. J., Stylo, M., Mutemeri, N., Singo, P., Twala, P., Mutemeri, I., Nakafeero, A., & Etui, I. D. (2023). Mercury and artisanal and small-scale gold mining: Review of global use estimates and considerations for promoting mercury-free alternatives. *Ambio*, 52(5), 833-852.
- Liu, L., Li, W., Song, W., & Guo, M. (2018). Remediation techniques for heavy metal-contaminated soils: Principles and applicability. *Science of the Total Environment*, 633, 206-219.
- Liu, S., Wang, X., Guo, G., & Yan, Z. (2021). Status and environmental management of soil mercury pollution in China: A review. *Journal of environmental management*, 277, 111442.
- Malehase, T., Daso, A. P., & Okonkwo, J. O. (2017). Initiatives to combat mercury use in artisanal small-scale gold mining: a review on issues and challenges. *Environmental reviews*, 25(2), 218-224.
- Mantey, J., Nyarko, K., Owusu-Nimo, F., Awua, K., Bempah, C., Amankwah, R., Akatu, W., & Appiah-Effah, E. (2020). Mercury contamination of soil and water media from different illegal artisanal small-scale gold mining operations (galamsey). *Heliyon*, 6(6).
- Mariki, E. E., Tungaraza, C., Chibunda, R. T., & Cohen, M. D. (2024). Elevated total mercury (THg) levels in water sources under the influence of artisanal and small-scale gold mining (ASGM) in Tanzania. *Environmental Monitoring and Assessment*, 196(11), 1036.
- Maulana, A., Harianti, M., & Prasetyo, T. B. (2023). Index of contamination/pollution factor, geo-accumulation and ecological risk in ex-gold mining soil contaminated with mercury. *Journal of Degraded & Mining Lands Management*, 10(4).
- Miller, C. L., Watson, D. B., Lester, B. P., Lowe, K. A., Pierce, E. M., & Liang, L. (2013). Characterization of soils from an industrial complex contaminated with elemental mercury. *Environmental research*, 125, 20-29.
- Mortazavi, S. (2018). Survey of modified hazard quotient, potential ecological risk factor and toxicity units of heavy metals in surface sediments of some wetlands of Iran. *Archives of Hygiene Sciences*, 7(4), 251-263.
- Mukherjee, A. B., Zevenhoven, R., Brodersen, J., Hylander, L. D., & Bhattacharya, P. (2004). Mercury in waste in the European Union: sources, disposal methods and risks. *Resources, Conservation and Recycling*, 42(2), 155-182.
- Nweke, M., & Ukpai, S. (2016). Use of enrichment, ecological risk and contamination factors with geoaccumulation indexes to evaluate heavy metal contents in the soils around Ameka mining area, South of Abakaliki, Nigeria. *Journal of Geography, Environment and Earth Science International*, 5(4), 1-13.

- Obrist, D., Kirk, J. L., Zhang, L., Sunderland, E. M., Jiskra, M., & Selin, N. E. (2018). A review of global environmental mercury processes in response to human and natural perturbations: Changes of emissions, climate, and land use. *Ambio*, 47, 116-140.
- Ogunyemi, M. K. (2023). *Spatial Analysis of Heavy Metal Content in Soil Peripheral Along Lagos-Ibadan Railway Route, South West, Nigeria* Kwara State University (Nigeria)].
- Pérez-Sirvent, C., Martínez-Sánchez, M., García-Lorenzo, M. d. I. L., Molina, J., & Tudela, M. (2009). Geochemical background levels of zinc, cadmium and mercury in anthropically influenced soils located in a semi-arid zone (SE, Spain). *Geoderma*, 148(3-4), 307-317.
- Raoilimanantsoa, N., Oremo, J., Akello, O., Majanga, W., Gunter, S., Ayodo, G., ... & Dorevitch, S. (2026). Metals in water used by artisanal and small-scale gold miners for gold-mercury amalgamation in Western Kenya. *Environmental Health*, 25(1), 10.
- Randall, P. M., & Chattopadhyay, S. (2013). Mercury contaminated sediment sites—An evaluation of remedial options. *Environmental research*, 125, 131-149.
- Rice, K. M., Walker Jr, E. M., Wu, M., Gillette, C., & Blough, E. R. (2014). Environmental mercury and its toxic effects. *Journal of preventive medicine and public health*, 47(2), 74.
- Ripanda, A. S., Rwiza, M. J., Nyanza, E. C., Njau, K. N., Vuai, S. A., & Machunda, R. L. (2021). A review on contaminants of emerging concern in the environment: a focus on active chemicals in Sub-Saharan Africa. *Applied Sciences*, 12(1), 56.
- Ritter, K. S., Paul Sibley, Ken Hall, Patricia Keen, Gevan Mattu, Beth Linton, Len. (2002). Sources, pathways, and relative risks of contaminants in surface water and groundwater: a perspective prepared for the Walkerton inquiry. *Journal of Toxicology and Environmental Health Part A*, 65(1), 1-142.
- Sanga, T. R., Maseka, K. K., Ponraj, M., Tungaraza, C., & Mwakalapa, E. B. (2023). Accumulation and distribution of mercury in agricultural soils, food crops and associated health risks: a case study of Shenda gold mine-Geita Tanzania. *Environmental Challenges*, 11, 100697.
- Schwartz, G. E., Sanders, J. P., McBurney, A. M., Brown, S. S., Ghosh, U., & Gilmour, C. C. (2019). Impact of dissolved organic matter on mercury and methylmercury sorption to activated carbon in soils: Implications for remediation. *Environmental Science: Processes & Impacts*, 21(3), 485-496.
- Semenkov, I., & Koroleva, T. (2019). International environmental legislation on the content of chemical elements in soils: guidelines and schemes. *Eurasian Soil Science*, 52, 1289-1297.
- Ssenku, J. E., Naziriwo, B., Kutesakwe, J., Mustafa, A. S., Kayeera, D., & Tebandeke, E. (2023). Mercury accumulation in food crops and phytoremediation potential of wild plants thriving in artisanal and small-scale gold mining areas in Uganda. *Pollutants*, 3(2), 181-196.
- Sun, Y., Li, H., Guo, G., Semple, K. T., & Jones, K. C. (2019). Soil contamination in China: Current priorities, defining background levels and standards for heavy metals. *Journal of environmental management*, 251, 109512.
- Tan, K. H. (2009). *Environmental soil science*. CRC Press.

Focus

- Taylor, H., Appleton, J., Lister, R., Smith, B., Chitamwebwa, D., Mkumbo, O., Machiwa, J. F., Tesha, A., & Beinhoff, C. (2005). Environmental assessment of mercury contamination from the Rwamagasa artisanal gold mining centre, Geita District, Tanzania. *Science of the Total Environment*, 343(1-3), 111-133.
- Tóth, G., Hermann, T., Da Silva, M. R., & Montanarella, L. (2016). Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment international*, 88, 299-309.
- Zhang, Y., Liu, Y., Niu, Z., & Jin, S. (2017). Ecological risk assessment of toxic organic pollutant and heavy metals in water and sediment from a landscape lake in Tianjin City, China. *Environmental science and pollution research*, 24, 12301-12311.