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Heavy metal contamination and health risks in Katoro's artisanal gold mining soils, Tanzania

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Keywords

Heavy metals; soil contamination; artisanal gold mining; geoaccumulation index; health risk; Tanzania

Abstract

This study assessed heavy metal contamination in surface soils from artisanal gold mining areas in Katoro, Tanzania, evaluating ecological and human health risks. Thirty-six soil samples were systematically collected from three mining villages (Bingwa, Isenye, and CCM) at varying distances ranging from 30 to 90 m from active mining pits alongside twelve control samples from a non-mining area for comparison purposes. Concentrations of Cr, Cu, Ni, Zn, Pb, and As in soil samples were analyzed using energy-dispersive X-ray fluorescence spectrometry (EDXRF). Results revealed severe contamination, with Cr (117–1255 mg/kg), Cu (81–104 mg/kg), and Ni (89–271 mg/kg) exceeding permissible limits. The geoaccumulation (Igeo) index indicated moderate to heavy contamination (Class II-III) for Cr, Cu and Ni. Meanwhile, the ecological risk assessment showed moderate risk (ERI = 154.41) across the study area highest being in Isenye village (ERI = 204.46). Health risk models identified ingestion as the primary exposure pathway, with hazard indices (HI) below 1, suggesting negligible non-carcinogenic risks. However, lifetime cancer risks for As (1.21×10^{-4}) and Cr (3.59×10^{-3}) surpassed acceptable thresholds (1×10^{-4}), indicating significant carcinogenic concerns, particularly for children. These findings underscore the urgent need for remediation and stricter regulations to mitigate contamination from artisanal mining activities.

Introduction

Artisanal and small-scale gold mining (ASGM) represents a vital economic sector in developing nations, yet it remains a significant source of environmental degradation and public health risks due to heavy metal contamination (WHO 2021). This is because ASGM represents a significant anthropogenic source of heavy metal contamination in soil systems. Particular concern is in geochemically mobile and toxic elements such as arsenic (As), chromium (Cr), cadmium (Cd), mercury (Hg) and lead (Pb) (UNEP 2022, Obiri et al. 2016). In Tanzania's Lake Victoria goldfields, Katoro mining district exemplifies the complex bio-geochemical challenges posed by uncontrolled ASGM activities (UNEP 2022). The mechanized ore processing combined with elemental mercury amalgamation techniques used in this area, have created multi-element

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contamination scenarios (Harari et al. 2008). Recent geochemical surveys have reported substantial enrichment of heavy metals in soils affected by ASGM activities (Ahmed et al. 2023, Johnson et al. 2022, Saad et al. 2020). Other reports indicate that the concentrations of priority pollutants in soils affected by ASGM activities exceed the concentration background levels by factors ranging from 10 to 100 (Basu et al. 2015, Neukum and Azzam 2009, Steckling et al. 2017). This is a worrying fact since the environmental consequences of ASGM activities can extend far beyond the immediate mining sites, affecting the surrounding agricultural lands and water resources.

Among the environmental concerns of ASGM activities is the heavy metal pollutants' persistence in the ecosystems and bio-accumulation in food chains, which may pose severe health threats, particularly to vulnerable populations such as children and pregnant women (Landrigan et al. 2023). For instance, Cr and As have been classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC) and are linked to lung cancer, skin lesions, and developmental disorders, particularly in children (IARC 2023). Yet, despite growing recognition of these hazards, comprehensive assessments of heavy metals contamination in soil and their associated health risks integrating modern analytical approaches remain scarce for Tanzania's ASGM regions (Pure Earth 2018) including Katoro district. This leaves a gap in evidence-based remediation and policy strategies. The problem is even exacerbated by Tanzania's regulatory framework, which is tailored for large-scale mining operations and fails to address the unique contamination patterns of ASGM. This study aims to establish the pedological impacts of ASGM activities in Katoro by providing a novel, holistic assessment of heavy metal contamination in Katoro's soils using a combination of geochemical analysis with ecological and health risk models.

The pedological impacts of ASGM activities manifest through three primary contamination pathways. The first pathway is the direct deposition of ore processing residues containing sulfide-associated metals like As, Cu and Zn. Another pathway is the atmospheric deposition of particulates such as Pb and Cd from crushing and grinding operations. Additionally, contamination can be caused by mercury from the amalgamation processes (Esdaile and Chalker 2018). The amalgamation process does not only release mercury but also mobilizes other toxic elements that are naturally present in gold-bearing ores (Rakete et al. 2022). Studies have shown that mining activities can increase the bioavailability of heavy metals which progressively contaminate the food chain through plant uptake and dust dispersion (Antoniadis et al. 2019).

The entrance of heavy metals in soil can alter the fundamental soil properties including its pH (typically acidifying to 4.5-5.5), organic matter content, and cation exchange capacity, thereby modifying metal speciation and bioavailability (Boussen et al. 2013). Moreover, accumulation of heavy metals in soil can lead to several ecological impacts like disruption of microbial communities and impaired plant growth development. A particular concern is on the potential effect of these contaminants to staple crops grown in the region, including maize and cassava. This is because, these crops are dietary mainstays for local communities around Katoro (Kachenko and Singh 2006). Contamination of staple crops would ultimately exacerbate the impact on human health, which occurs through complex exposure pathways (Mwesigye et al. 2016). It follows that; assessments of risks associated with mining affected soils must account for both ecological and human health endpoints to minimize the impacts of heavy metals accumulation (U.S. Environmental Protection Agency 2020).

The health implications of chronic heavy metal exposure are particularly severe in mining communities. For example, Chromium (VI) and arsenic are classified as Group 1 carcinogens by IARC (2012), with well-documented associations with lung cancer, skin lesions, and developmental disorders (Kapaj et al. 2006). Reports show that children in mining communities face disproportionate risks due to their higher metabolic rates, hand-to-mouth behaviors, and developing physiological systems (U.S. Environmental Protection Agency 2020). Meanwhile, workers involved in mercury amalgamation have been reported to exhibit symptoms indicative of chronic mercury intoxication, such as fine tremors, ataxia, and altered tendon reflexes (Appleton et al. 2005). The study revealed high mercury concentrations in blood, hair, and urine samples taken from workers around Rwamagasa area with amalgam burners showing the most elevated levels. Another study revealed significant increase in blood lead levels in pregnant women living around gold mining area in Rwamagasa (Thomas et al. 2024). These findings highlight the significant exposure risks to lead in mining-affected regions and the need for a comprehensive assessment of risks posed by the presence of heavy metals in soils from the areas influenced by ASGM activities.

In assessing the risks posed by heavy metal accumulation in soil, several indices including ecological risks and potential human effect are deployed to evaluate the extent to which mining activities affect the soil. Indices like the geo-accumulation index (Igeo), provide a quantitative measure of anthropogenic metal enrichment relative to lithogenic background level (Li et al. 2004). The ecological risk indices (ERI) incorporate metal toxicity factors to evaluate impacts of heavy metals pollution to the ecosystem (Wang et al. 2006). The heavy metal pollutants can find their way into the human body through ingestion, inhalation or dermal absorption. As some metals are known to be carcinogenic, another important health index is the lifetime cancer risk index (LCRI) which is important for checking the carcinogenicity of the contaminants. Recent studies in similar ASGM regions have demonstrated carcinogenic risks from As and Cr exceeding the USEPA threshold of 10^{-4} by factors ranging from 3 to 10 resulting to several adverse impacts (Bempah and Ewusi 2016). Therefore, of soil around Katoro may prove to be seriously detrimental to the populations around.

Some of the consequences of heavy metal contamination in soil are already observed in Katoro. Preliminary field observations indicate visible signs of environmental stress, such as vegetation die-off in the vicinity of ore processing sites and noticeable soil discoloration in mining zones. These indicators are consistent with documented impacts of heavy metal toxicity, which often include inhibited plant growth, altered soil chemistry, and reduced microbial activity (Bempah and Ewusi 2016, Esdaile and Chalker 2018). Besides, agricultural yields in some areas have noticeably declined threatening food security for communities that live on subsistence farming. These impacts demonstrate how unregulated ASGM activities can create vicious cycles where short-term economic gains lead to long-term environmental and health costs that ultimately undermine community wellbeing.

Addressing this multifaceted problem requires a holistic scientific framework that integrates environmental monitoring with public health analysis (Basu et al. 2015). That is, there is a critical need for research that not only quantifies contamination levels but also maps the pathways through which heavy metals migrate from mining sites into surrounding communities (Long et al. 2015). Such investigations must extend beyond mere concentration data to consider how factors like soil characteristics, land use practices, and local behaviors influence the exposure risks. Therefore, the current study focused on comprehensively evaluating the heavy metal contamination in Katoro's soils, employing multiple analytical approaches to assess both environmental and health risks. By integrating environmental and public health perspectives, this research offers actionable insights for policymakers to reform ASGM regulations, prioritize remediation, and safeguard community health. The study thus bridges a critical gap in data, supporting sustainable mining practices while addressing Katoro’s pressing environmental health challenges. Results from this study will provide evidence that would form the foundation for designing specific interventions for soil remediation, land restoration and health education campaigns. Such interventions will prove invaluable for protecting both ecological integrity and human health, while ensuring that the economic benefits of ASGM are sustained. Moreover, the obtained data will provide empirical evidence to inform Tanzania's evolving ASGM regulatory framework.

Materials and Methods

The assessment of heavy metal contamination in soil requires meticulous sampling strategies, careful sample preparation, and robust analytical techniques to ensure data reliability. This study implemented a comprehensive protocol for soil sample collection, preparation, and analysis in the Katoro mining district of Tanzania, incorporating stringent quality assurance measures at each stage.

The Study Area

This study was conducted at Katoro area which is located in Geita region in Nothern Tanzania. The region is bordered to the East by Mwanza region and Nyang'hwale district, to the South by Shinyanga region and Mbogwe District, and to the West by Chato District. According to the 2022 census, the population of the region is 2,977,608 of which the population of Katoro was approximately 16,284 people with 7,713 males and 8,571 females. Katoro is located at latitude 3°1.217' S and Longitude 31o53.75′ E, 35 km from Geita town center. Apart from being the hub of ASGM activities in Geita, people in Katoro also practice agricultural activities. Within Katoro, samples were collected from Rwamagasa center, which is also known as Lwamgasa, shown by the satelite picture in Figure 1.

Figure 1: Satellite picture showing the location of Katoro and Rwamagasa area (Google Earth Satellite)

Sample Collection

The sample collection strategy was designed to capture spatial variability of heavy metal concentrations around active mining pits. Mining pits located at three mining villages (Bingwa, Isenye, and CCM) were selected as primary sampling locations, with soil samples collected at increasing distances (30 m, 60 m, and 90 m) from a mining pit as shown in Figure 2 to evaluate contamination gradients. A control site located approximately 25 km from mining activities was included for baseline comparison.

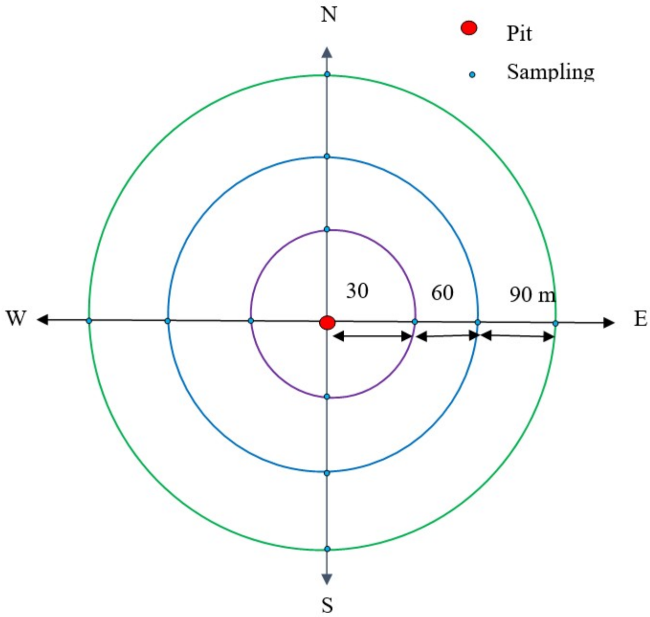

Figure 2: Sketch showing the sample collection points around the mining pit

At each sampling point, a composite sampling approach was employed to account for micro-scale heterogeneity. Four sub-samples (750 g each) were collected from a 1 m^2 area at a consistent depth of 15 cm using pre-cleaned stainless-steel tools. These subsamples were thoroughly homogenized in the field to create a representative composite sample. The sampling design incorporated cardinal directions (North, South, East, West) around each pit to assess directional contamination patterns. In order to discover the contribution of ASGM activities to the soil contamination around Katoro, a set of 12 soil samples were collected from control areas. These control samples were randomly collected from a region located approximately 25 km away from the pits, where neither agricultural, industrial nor mining activities are practiced.

Immediately after collection, samples were placed in inert polyethylene bags to prevent contamination and stored in coolers with ice packs during transportation. Each sample was labeled with unique identifiers and precise GPS coordinates which were recorded using a Garmin GPSMAP 64s device with ±3 m accuracy. Field blanks consisting of pre-washed quartz sand were processed alongside actual samples to monitor potential contamination during sampling and handling procedures. All the packed samples were then transported to the Tanzania Atomic Energy Commission (TAEC) laboratory in Arusha for analysis.

Sample Preparation

Upon arrival at the TAEC laboratory, a systematic samples preparation procedure was carried out. The first step involved oven drying at 45-50°C for 24 hours in acid-washed porcelain dishes to remove moisture while minimizing volatile element loss. Dried samples were then disaggregated using an agate mortar and pestle to avoid metal contamination from grinding equipment. The homogenized samples were sieved through a

50 μm nylon mesh to obtain consistent particle size distribution, following ISO 11464:2006 guidelines. This particle size was selected to optimize analytical sensitivity while maintaining representativeness of bulk soil composition (Lugendo et al. 2013). Approximately 100 g of each sieved sample was archived as a reference material for potential future analysis.

For X-ray fluorescence analysis, 4 g aliquots of the homogenized powder were pressed into pellets using a hydraulic press at 15 bar pressure (Lugendo et al. 2013). The pellets were formed to 15 mm thickness and 32 mm diameter to match the sample holder specifications of the EDXRF instrument. Each pellet was visually inspected for uniformity and surface defects before analysis. The pellets were then placed in sample holders and inserted in EDXRF machine for elemental analysis.

Elemental Analysis

Elemental analysis was performed using a Spectro Xepos EDXRF system with serial number 4R0138. The system is equipped with a Pd anode X-ray tube and operated by X-lab ProTM software. The instrument was configured with three secondary targets to optimize excitation conditions for different element groups: a highly oriented pyrolytic graphite (HOPG) target for light elements (Na-V), molybdenum (Mo) target for mid-range elements (Cr-Zr and Pr-U), and an aluminum oxide (Al_2O_3) Barkla target for high-energy elements (Y-Ce). Each sample was analyzed for 15 minutes under three different excitation conditions (25 kV/0.5 mA, 35 kV/0.75 mA, and 50 kV/1 mA) to ensure optimal detection across the entire elemental range. The spectrometer was calibrated using certified reference materials (NIST 2710a, NIST 2709, and IAEA Soil-7) that encompassed the expected concentration ranges in environmental samples. The elemental composition of the samples were determined from spectra of the respective samples using the X-lab proTM software. Each spectrum was used to calculate the concentration of elements in a given sample and the Minimum Detection Limit (MDL) of the instrument for the respective element.

Quality Assurance and Quality Control

A comprehensive quality assurance program was implemented throughout the analytical process. In this program, the instrument performance was verified daily using calibration check standards, with recalibration performed whenever the drift exceeded 5%. The detection accuracy was verified by analyzing the reference standard after the analysis of every ten samples. The analytical precision, expressed as relative standard deviation (RSD) of duplicate measurements, was maintained below 10% for all reported elements. Recovery rates for spiked samples ranged between 85-115% for target analytes, meeting acceptable criteria for environmental analysis, while any potential contamination was monitored using the blank sample analysis for every batch. Moreover, all the obtained analytical data were subject to rigorous validation before interpretation. Elemental concentrations below the method detection limit were reported as "<MDL" and excluded from statistical analysis. Outliers were identified using Dixon's Q-test at 95% confidence level. The final results were reported as mean concentrations with associated measurement uncertainties based on counting statistics and calibration errors.

Index of geo-accumulation

The index of geo-accumulation (I_{geo}) was introduced into sediment geochemistry to assess the degree of heavy metal contamination in sediments. Yet, the index is also useful in evaluating the heavy metal contamination in soils. This index is computed by using Equation (1), according to Li et al. 2016.

$$I_{geo} = \log 2 \frac{C_{HMS}}{1.5 \times GBV} \quad (1)$$

Where C_{HMS} is the concentration of heavy metals in soils and GBV is the geochemical background value. The constant 1.5 accounts for the natural fluctuations in the content of a given substance in the environment. The I_{geo} for each metal is used as the criteria to decide whether the sample is contaminated or not. The criteria is described in Table 1.

Table 1: Classification of the heavy metal contamination status of the soil

SN	I_{GEO} VALUE	CONTAMINATION STATUS
1	$I_{geo} \leq 0$	Uncontaminated to moderate contamination
2	$0 < I_{geo} \leq 1$	Moderate contamination
3	$1 < I_{geo} \leq 2$	Moderate to heavy contamination
4	$2 < I_{geo} \leq 3$	Heavy contamination
5	$3 < I_{geo} \leq 4$	Heavy to extreme contamination
6	$4 < I_{geo} \leq 5$	Extreme contamination

Ecological risk index

The potential risks associated with heavy metal pollution in soil was evaluated using the ERI. In this evaluation, the ecological risk of heavy metals is classified into five levels according to the values of the ecological risk factor, E_r^i and the ecological risk index ERI calculated using Equations (2) to (4) respectively. The criteria used to classify the ecological risks along with the risk classifications are presented in Table 2.

$$ERI = \sum_{i=1}^{n} E_r^i \quad (2)$$

$$E_r^i = T_r^i x C_f^i \quad (3)$$

$$C_f^i = \frac{C^i}{C_n^i} \quad (4)$$

Where C_f^i is the pollution coefficient of single metal, C^i is the measured concentration of the element in the sample, C_n^i is the background concentration of the element in soil, T_r^i is the toxicity factor of a given element, E_r^i is the potential ecological risk of a given element and ERI is the total ecological risk due to all elements. The T_r^i values for As, Ni, Cu, Pb, Cr, and Zn are 10, 5, 5, 5, 2, and 1, respectively (Huang et al. 2019).

Table 2: Classification criteria of the ecological risks of heavy metal contamination in soil

SN	E_r^i	Risk classification	ERI	Risk classification
1	$E_r^i < 40$	Low risk	$ERI < 150$	Low risk
2	$40 < E_r^i < 80$	Moderate risk	$150 < ERI < 300$	Moderate risk
3	$80 < E_r^i < 160$	Considerable risk	$300 < ERI < 600$	Considerable risk
4	$160 < E_r^i < 320$	High risk	$ERI > 600$	High risk
5	$E_r^i > 320$	Very high risk		

Health risk assessment of heavy metals in soils

Health risk assessment is used to describe the non-carcinogenic and carcinogenic risks to humans due to chemical exposure. Generally, humans are exposed to soil metals through three main corridors: ingestion, inhalation, and dermal contact. US EPA suggested a fundamental method for estimating the doses received through ingestion, dermal, and inhalation (U.S. Environmental Protection Agency 2011). In this study, the average daily exposure dose (mg/kg/day) of potentially toxic metals via ingestion, dermal contact, and inhalation for both adults and children were computed using Equations (5) to (7).

$$ADD_{ingestion} = \frac{CMS \times IR \times ED \times EF}{ABW \times AET} \times CF \quad (5)$$

$$ADD_{dermal} = \frac{CMS \times SA \times SAF \times DAF \times EF \times ED}{ABW \times AET} \times CF \quad (6)$$

$$ADD_{inhalation} = \frac{CMS \times IHR \times ED \times EF}{ABW \times AET \times PEF} \quad (7)$$

Where ADD is the average daily dose (mg/kg/day), CMS is the concentration of metal in soil (mg/kg), IR and IHR are the ingestion and inhalation rates of metals in soil, respectively (mg/ day), ED is the exposure duration (year), and EF is the exposure frequency (day/year). ABW and AET represent the average body weight (kg) and average exposure time (year), respectively. CF is the conversion factor (10^{-6} kg/ mg), SA is the exposed skin surface area (cm^2), SAF is the skin adherence factor (kg/cm^2 day), DAF is the dermal absorption factor, and PEF is the particle emission factor (m^3/kg).

The reference dose (RfD) which serves as the benchmark for assessing potential non-carcinogenic chronic health risks was deployed in this study. When the estimated exposure dose of a specific contaminant exceeds the RfD, there is an increased likelihood of adverse health effects. This relationship was typically quantified using the Hazard Quotient (HQ) and Hazard Index (HI). The HQ represents the ratio of the exposure dose to the RfD for an individual metal, while the HI is the cumulative sum of HQs for multiple exposure pathways or elements, reflecting the overall non-carcinogenic risk posed by soil contaminants. The HQ and HI were calculated using Equations (8) and (9).

$$HQ = \frac{ADD}{RfD} \quad (8)$$

$$HI = \sum \left(HQ_{ingestion} + HQ_{inhalation} + HQ_{dermal}\right) \quad (9)$$

Note that, RfD is the reference dose in (mg/kg day) adopted from US EPA 2001. If the value of HI < 1, no significant risk of non-carcinogenic effects is expected to occur. When HI > 1, there is a possibility of non-carcinogenic effects with the probability increasing with the increasing HI value (US EPA 2005). Meanwhile, the carcinogenic risk was calculated using Equations (10) and the lifetime cancer risk (LCR) which is the summation of the cancer risk (CR) from each exposure corridor was determined using Equation (11).

$$CR = ADD \times CSF \quad (10)$$

$$LCR = \sum CR\left(ingestion + inhalation + dermal\right) \quad (11)$$

CSF is the cancer slope factor and its values for Cr, Pb, and As are 0.5, 0.0085 and 1.5 mg/kg/day (US EPA 2001). The acceptable threshold value for CR is 1.0×10^{-04}, while the tolerable LCR for regulatory purposes ranges from 1.0×10^{-06} to 1.0×10^{-04} (U.S. Environmental Protection Agency 2020).

Results and Discussion

Heavy metal concentration in soil

The elemental composition of soil samples from Bingwa, Isenye and CCM villages as well as the soil samples from the control regions, were obtained from the EDXRF spectrometer. Heavy metals with significant concentrations were found to be Cr, Zn, Cu, Pb, Ni and As. The mean concentrations of these elements in soils from all villages and from the control region are presented in Table 3.

Table 3: The mean concentrations of heavy metals in soil samples from the study area

Element	Concentration (µg/g)			
	Bingwa (n = 12)	**Isenye (n = 12)**	**CCM (n = 12)**	**Control soil (n =12)**
Cr	117.150 ± 5.901	1254.870 ± 63.208	240.340 ± 12.106	64.420 ± 3.245
Zn	60.970 ± 3.071	73.450 ± 3.700	42.180 ± 2.125	16.750 ± 0.844
Cu	97.090 ± 4.890	81.070 ± 4.083	104.360 ± 5.257	10.710 ± 0.539
Pb	11.100 ± 0.559	11.240 ± 0.566	14.400 ± 0.725	9.880 ± 0.498
Ni	89.010 ± 4.483	271.300 ± 13.665	88.770 ± 4.471	13.930 ± 0.702
As	5.760 ± 0.290	4.020 ± 0.202	8.300 ± 0.418	1.990 ± 0.100

From Table 3, it is clearly observed that the concentrations of all heavy metals in soils from all three villages are significantly higher than the respective concentrations in soil from the control sample. Special concerns are on Cr, Ni, Cu and As whose concentrations in soil around the mining pits are very high compared to the concentrations in the soil from the control area. Such findings give a hint on the heavy metals pollution that is caused by the ASGMA in Katoro. Meanwhile, the concentrations of different elements in soils seem to vary depending on the area where the soil sample was obtained. This signals of different levels of heavy metal pollution in different areas is probably due to different mining methods and practices.

A significant concern is on the levels of As in soil from CCM village as it is about 4 times higher than the concentration in the control soil. As is known to occur naturally in soils as a result of the weathering of the parent rocks. However, its concentrations in soil can be enhanced by anthropogenic activities like artisanal mining activities as well as the use of arsenic-based pesticides and fertilizers. Following its adverse effect to human being, the Canadian Environmental Quality Guidelines (CEQG) has set maximum permissible limit for As concentration in soil to be 12 mg/kg (Canadian Council of Ministers of the Environment (CCME) 2002). Although the observed concentrations of As in soil from all villages is below the recommended limit, its higher values compared to the control soil alarms about the soil pollution caused by anthropogenic activities like gold mining.

Another element of concern was found to be Cr whose concentration levels range from 117. 15 to 1254.87 mg/kg, with an average of 537.45 mg/kg. The maximum concentration of 1254.86 mg/kg was found in soil from Isenye village with the minimum concentration found in Bingwa village. Yet, in both villages, the concentration of Cr in soil exceeds the maximum permissible limit of 60 mg/kg recommended by CEQG (2002). On the other hand, the concentrations of Zn in katoro soil was observed to range from 42.18 to 73.45 mg/kg, with an average concentration of 58.87 mg/kg. In this case, the concentration of Zn in Katoro soil is lower than the recommended permissible concentration of 200 mg/kg. This means Zn concentration in Katoro soil is not a problem and can contribute to the positive impacts which include playing a role in physical growth and development, functioning of the immune system, reproductive health, sensory functions as well as plant growth and animals (Krishna and Govil 2005).

The concentration of Cu in all soil samples from the mining pits was higher than the respective concentration in the control soil. Table 3 shows that the concentration of Cu ranged from 81.07 to 104.36 mg/kg in all soil samples. All these concentrations are higher than the permissible limit of 63 mg/kg set by CEQG 2002. This is a concern because, although Cu is an important trace element for the support of good health for human beings, exposure to high doses can be detrimental. For example, chronic exposure to Cu dust could result in undesirable conditions, such as nausea, headaches, and diarrhea. Besides, eyes, nose, and mouth irritations may occur if a person is over-exposed to Cu dust. Meanwhile, Ni which is the 23rd common element of the earth's crust was also found to be present in Katoro soil. Its concentrations ranged from 88.77 to 271.30 mg/kg, with a mean of 149.69 mg/kg. In all cases, the measured concentrations of Ni in all soil samples were found to exceed the maximum permissible limit of 50 mg/kg. This is alarming since exposure to high concentrations of Ni and Cr has been reported to cause lung cancer (Rattan et al. 2005).

Generally, the findings of this study show that, except for the case of Cr and Ni, the concentrations of heavy metals in Katoro soils are below the permissible limits. This means, despite being the hub for artisanal ASGM in Geita, Katoro soil is yet to be significantly affected by these mining activities. Nevertheless, glimpse of heavy metals pollution have been observed signifying the need for strategic measures to sustain the environment.

Geo-accumulation of heavy metals in Katoro soil

The geo-accumulation index (Igeo), a widely recognized tool for assessing heavy metal pollution in soils and sediments, was employed in this study to evaluate the extent of contamination in the Katoro region. This metric enables in differentiating between natural background levels and anthropogenic contributions to heavy metal concentrations and has been extensively applied in global contexts to assess contamination severity (Alshahri and El-Taher 2018). In the current study, positive Igeo values were observed for most of the analyzed metals including Cr, Cu, Zn, Ni, Pb, and As as shown in Figure 3. These positive Igeo values indicate the presence of anthropogenic contamination in Katoro soil. Based on the Igeo classification system by Müller (1969), which categorizes contamination from Class 0 (uncontaminated) to Class VI (extremely contaminated), the soils in Katoro fall predominantly within Class I (unpolluted to moderately polluted) and Class III (moderately polluted) for various elements.

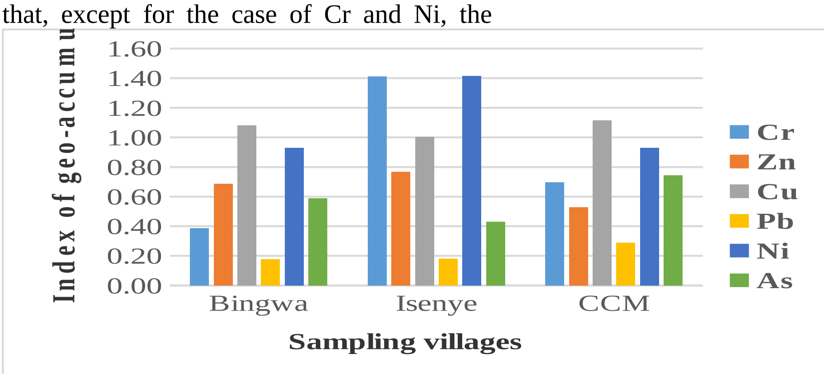

Figure 3: The geo-accumulation indices for various metals in the study areas

Figure 3 shows that the Igeo values for As, Pb and Zn ranged from 0.43 to 0.75, 0.18 to 0.29, and 0.53 to 0.77 respectively, with mean values of 0.59, 0.22, and 0.66. This indicates unpolluted to moderately polluted conditions across the sampling locations. Cr and Ni, however, showed higher contamination levels with the mean Igeo values of 0.83 and 1.09, respectively. This means, these elements fall in pollution Class II to III. Contamination of soil by these elements is potentially caused by mining-related inputs and other associated anthropogenic activities. Meanwhile, Cu exhibited a consistent Igeo range between 1.00 and 1.11, hence falling within the pollution Class III (moderately polluted). These elevated levels could be attributed to activities typically related to ASGM, including ore crushing and amalgamation processes that frequently mobilize base metals along with target minerals.

Overall, the geo-accumulation profile reveals that metal contamination in Katoro soils is not uniform and varies significantly among elements, with Cr, Ni, and Cu representing the highest contamination concerns. The elevated concentrations of chromium (Cr), copper (Cu), and nickel (Ni) in Katoro's soils indicate substantial anthropogenic pollution from mining operations. Chromium levels, reaching up to 1254.87 mg/kg (20 times higher than control samples), are particularly alarming given its toxicity in hexavalent form (Cr (VI)), which is highly mobile and carcinogenic. The geoaccumulation index (Igeo) classified Cr and Ni contamination as moderate to heavy suggesting long-term accumulation due to continuous mining activities. It follows that, in the long run, such pollution may impair microbial activity in soil, reducing organic matter decomposition and nutrient cycling. Studies have shown that Cr (VI) inhibits nitrogen-fixing bacteria, diminishing soil fertility (Giller et al., 2021). On the other hand, the acidic soil conditions (pH 4.5–5.5) enhance metal leaching, threatening nearby water bodies. This aligns with research in Zambia, where ASGM runoff increased dissolved metal loads in rivers (UNEP, 2023).

In any case, the presence of moderate contaminated zones from the heavy metals underscores the need for targeted remediation efforts and continued environmental monitoring. Interestingly, the observed patterns are consistent with findings from similar mining-impacted regions, where elevated Igeo values are typically associated with localized anthropogenic inputs (Alshahri and El-Taher 2018). This shows the need for evaluating the contamination indices in mining prone areas not only for risk assessments but also for guiding environmental management and informing policymaking bodies.

Ecological risks

To assess the potential ecological risks posed by heavy metals (Zn, As, Cr, Cu, Ni, and Pb) in the soil of the study area, the ecological risk factors (E_r^i) and Ecological Risk Indices (ERI) were employed. While E_r^i is used to indicate the risk posed by an individual element, ERI is widely used to evaluate the potential ecological risk caused by pollutants like heavy metals and their impact to an ecological system. The ERI assessment takes into account the toxicity effect of the individual elements alongside their measured concentrations in soil as compared to the reference values of the heavy metal in the Earth's crust as described by Equations (2) to (4). The results of this analysis revealed significant variations in the ecological risk factors (E_r^i) among elements found in soil from the sampled villages (Bingwa, Isenye, and CCM). Nevertheless, the ERI values showed that the ecological risk is low for Bingwa and CCM but moderate for Isenye village as shown in Table 4.

Table 4: Potential ecological risk factors and ecological risk indices of heavy metals found in soil from the study area

Sampling villages	**Potential ecological risk factor (E_r^i)**						**ERI**	**Risk classification**
	Zn	As	Cr	Cu	Ni	Pb		
Bingwa	3.640	28.945	3.637	45.327	31.949	5.617	119.115	Low risk
Isenye	4.385	20.201	38.959	37.848	97.380	5.688	204.461	Moderate risk
CCM	2.518	41.709	7.462	48.721	31.863	7.287	139.560	Low risk

On average, the ecological risk factors for individual heavy metals in soils of the study area decreased in the order of Ni > Cu > As > Cr > Pb > Zn. Notably, Ni exhibited the highest risk, with values ranging from 31.86 to 97.38 and a mean of 53.73. This shows that Ni contamination in soil poses a considerable risk to the ecology around the study area. The risk is probably due to the high toxicity of the element and its elevated concentrations in soil relative to recommended limits. Yet, As and Cu also pose notable risks, with mean risk factor values of 30.29 and 43.97, respectively. It is also interesting to notice the variability of these elements' concentrations in soil across the study area as indicated by the corresponding risk factor ranges of 20.20 to 41.71 for As and 37.85 to 48.72 for Cu. In contrast, Zn and Pb exhibited minimal ecological risks, with maximum risk factor values below 8, making them fall in the category of "low risk" elements. Meanwhile, Cr showed a wide range of the ecological risk factor (3.637–38.959), with its risk levels varying from low to moderate depending on the location. The dominance of Ni, Cu, and As in contributing to ecological risk aligns with findings from other studies, which have identified these metals as significant pollutants in similar environments (Luo et al. 2011; Taylor et al. 2005). Furthermore, the low risk associated with Zn and Pb is consistent with their relatively lower toxicity and concentrations.

The ERI values, calculated as the sum of all single ecological risk factors, varied significantly among the villages. Bingwa and CCM were found to be at low risk levels with ERI values of 119.115 and 139.560, respectively. However, Isenye was found to be at a moderate risk level as its corresponding ERI value was 204.461. This high value of ERI can be attributed to the high concentrations of Ni and Cr in Isenye soil. In any case, the average ERI value across the study area was 154.410, confirms the moderate ecological risks across Katoro with Isenye village (ERI = 204.46) reaching concerning levels. Such degradation demands immediate remediation to prevent irreversible damage to agricultural lands and aquatic ecosystems. The variability of E_r^i and ERI values across villages highlights the spatial heterogeneity of heavy metal contamination across the study area emphasizing on the need for targeted mitigation strategies in high risk areas.

Health Risk Assessment

A comprehensive assessment of human health risks associated with human exposure to heavy metals present in Katoro soils revealed distinct patterns of non-carcinogenic and carcinogenic risks through different exposure pathways and population groups. The non-carcinogenic risks posed by human exposure to heavy metals in Katoro soil through ingestion, inhalation and dermal contact are presented in Table 5.

Table 5: Non-carcinogenic risks due to heavy metals' exposure in Katoro soil via ingestion, inhalation and dermal contact for adult and children.

	Adults				Children			
	HQ Values			HI ($\times 10^{-4}$)	HQ Values			HI ($\times 10^{-3}$)
	Ingestion ($\times 10^{-4}$)	Dermal contact ($\times 10^{-5}$)	Inhalation ($\times 10^{-9}$)		Ingestion ($\times 10^{-3}$)	Dermal contact ($\times 10^{-5}$)	Inhalation ($\times 10^{-8}$)	
Cu	33.630	34.10	31.650	37.05	31.39	66.97	59.09	32.06
Ni	106.90	121.00	97.70	119.00	99.80	23.66	182.4	102.2
Zn	2.803	4.27	2.638	3.23	2.616	8.372	4.925	2.700

The hazard quotients (HQs) for Cu, Ni, and Zn exposure demonstrated consistent patterns across all evaluated pathways. The exposure hierarchy followed ingestion > dermal contact > inhalation for both adults and children as observed in Table 5. This pattern reflects the predominant role of soil ingestion as the primary exposure route in contaminated environments. Notably, children exhibited significantly higher exposure risks compared to adults, with HQ values approximately one order of magnitude greater across all pathways. For instance, the ingestion HQ for Ni ranged from 23.66×10^{-5} to 182.40×10^{-8} in children, compared to 121×10^{-5} to 97.7×10^{-9} in adults. This disparity aligns with established understanding of children's heightened vulnerability due to physiological factors and behavioral patterns. However, the cumulative hazard index (HI) values for all metals remained below the US EPA threshold of 1.0 as seen in Table 5. This suggests that non-carcinogenic risks from Cu, Ni and Zn are currently within acceptable limits. Yet, the relatively elevated HI values for Ni, which reach 10.22×10^{-3} in children, warrant attention, particularly given the metal's known toxicological profile.

Carcinogenic risk assessment

The evaluation of carcinogenic risks posed by the exposure to elevated concentrations of heavy metals in Katoro soil was performed using the Cancer Risks (CR) and the Lifetime Cancer Risk (LCR) parameters. The results of this evaluation show concerning CR and LCR values for some heavy metals present in Katoro soils. Table 6 shows the carcinogenic risks of exposure to heavy metals in Katoro soil through ingestion, inhalation or dermal contact.

Table 6: Carcinogenic risks of exposure to heavy metals in Katoro soil via ingestion, dermal contact and inhalation for adult and children

	Adults				Children			
	CR Values			LCR ($\times 10^{-7}$)	CR Values			LCR ($\times 10^{-6}$)
	Ingestion ($\times 10^{-7}$)	Dermal contact ($\times 10^{-9}$)	Inhalation ($\times 10^{-11}$)		Ingestion ($\times 10^{-6}$)	Dermal contact ($\times 10^{-9}$)	Inhalation ($\times 10^{-11}$)	
As	129.1	393	121.5	133.1	120.5	192.9	338.1	120.7
Cr	3839	117	3613	3956	3583	5733	10050	3589
Pb	1.487	4.53	1.400	1.533	1.388	2.221	3.893	1.390

Chromium (Cr) emerged as the most significant carcinogenic hazard, with LCR values of 3589 x 10^{-6} for children and 3956×10^{-7} for adults. These values consistently exceed the US EPA's acceptable threshold of 1.0×10^{-4}. These elevated risks are particularly alarming given that Cr(VI) is a known human carcinogen with well-documented health effects (US EPA 2001) particularly lung and nasal cancer

(IARC 2023). Meanwhile, despite having a lower concentration than Cr, Arsenic (As) demonstrated borderline carcinogenic risks for children with LCR value of 1.21×10^{-4} , which is slightly higher than the threshold limit. Exposure to this element is linked to skin lesions and bladder cancer (WHO, 2022). In contrast, Pb posed negligible carcinogenic risks across all population groups. The population specific risk patterns mirrored those observed for non-carcinogenic effects, with children consistently exhibiting higher vulnerability. These results warn of the danger that can be caused by heavy metal contaminations in soil. Children face disproportionate risks due to higher metabolic rates, frequent soil ingestion, and developing physiological systems. Without intervention, prolonged exposure could lead to generational health crises, including cognitive impairments and developmental disorders. Therefore, it is important to monitor the activities such as ASGM and other anthropogenic activities, which lead to the contamination of soil with heavy metals.

Comparative Analysis with Global ASGM Regions

The heavy metal contamination patterns observed in Katoro's artisanal mining soils exhibit both similarities and striking differences when compared to other ASGM regions worldwide. This reveals critical insights into the geochemical fingerprints of mining pollution, the effectiveness of regulatory approaches, and region-specific health risks that can inform targeted remediation strategies. For instance, Chromium levels reaching 1,255 mg/kg in Katoro soil distinguishes the region from many well-studied ASGM areas. While mercury (Hg) dominates pollution studies in Peruvian and Brazilian ASGM sites (Esdaile and Chalker, 2018), Katoro shows Cr concentrations 15-20 times higher than these regions. This likely stems from differences in ore geology, as Tanzania's Lake Victoria Greenstone Belt contains chromite-rich formations absent in Andean deposits. On the other hand, Ghana's Obuasi mines (Bempah et al., 2023) has been reported with comparable Cr enrichment (800-1,100 mg/kg), suggesting similar geochemical processes in Archean gold deposits. However, Katoro's Cr (VI) levels show greater mobility due to acidic soils as compared to Ghana's near-neutral soils.

Another distinctive feature of the Katoro ASGM is presented by the elevated concentrations of Ni (271 mg/kg) and Cu (104 mg/kg) as it is unusual for most ASGM. Katoro's Ni levels in soil rival those near industrial smelters, implying that rudimentary ore processing may generate industrial-scale pollution. This Ni-Cu cocktail creates unique exposure risks as chronic Ni exposure correlates with pulmonary fibrosis and dermatitis (ATSDR 2023), conditions already reported anecdotally in Katoro's clinics. Besides, unlike many ASGM hotspots, Katoro shows relatively low Hg contamination (0.8-1.2 mg/kg) compared to (25-150 mg/kg) in Brazilian ASGM soils (UNEP 2022) and (8- 45 mg/kg) in Compostela Valley (Appleton et al. 2023). Yet, the co-occurrence of Hg with Cr/Ni in Katoro may exacerbate toxicity through synergistic effects poorly understood in current risk models. This indicates that, people around Katoro ASGM may be at a greater risk caused by the soil pollution due to ASGM activities compared to other regions with similar activities.

Conclusion

This study conducted a comprehensive assessment of heavy metal contamination in surface soils from the artisanal gold mining areas of Katoro and the associated ecological and public health consequences. The findings reveal alarming chromium, nickel, and copper pollution exceeding international safety thresholds, with geoaccumulation indices confirming moderate to heavy contamination, clearly indicating the environmental impact of ASGM activities in Katoro. Besides, the ecological risk assessments identified moderate ecological risks (ERI = 204.461), particularly in Isenye village, signaling urgent need for intervention. Notably, lifetime cancer risks for chromium (3.59×10^{-3}) and arsenic (1.21×10^{-4}) were found to surpass the acceptable threshold level of 1.0×10^{-4}, disproportionately affecting children through soil ingestion pathways. Comparative analysis highlights Katoro's distinct contamination profile marked by exceptional chromium enrichment that diverges from typical mercury dominated ASGM regions. This underscores the demand for immediate actions including soil remediation in high risk zones, regulatory reforms addressing non-mercury metals and community health education. The study provides a model for assessing ASGM impacts in similar geological settings, emphasizing that sustainable mining policies must account for locally-specific contamination patterns to effectively protect both ecosystems and vulnerable populations. Furthermore, following the high concentrations of chromium and nickel in Katoro's soil, Tanzania's mining regulations should strive to integrate chromium and nickel monitoring to reduce contamination. As the current study only focused on soil contamination, future research must investigate metal bioavailability in staple crops and evaluate low-cost remediation techniques for tropical soils.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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