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Geochemistry of Potentially Toxic Elements in Soil and Sediments of a Tanzanian Small-Scale Gold Mining Area

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Abstract

Small-scale gold mining is linked to significant environmental pollution by potentially toxic elements (PTEs). However, research on the pollution caused by such mining activities remains insufficient especially in developing countries. In the present study, a systematic investigation assessed the pollution and level of ecological risk of PTEs in soil and stream sediments in an active small scale gold mining area of Isanga, in Nzega, Tanzania. Samples amounting to 16 soil and 20 sediment were gathered from the study area and analyzed for five PTEs concentrations (As, Cd, Cr, Hg and Pb) using the AAS method. The contamination level and ecological risk were assessed using several pollution indices. The results suggest that the assessed environmental systems of the Isanga mining area and its vicinities are lowly contaminated by PTEs and have a low potential to pose ecological risks. Hg and Cd with mean concentrations of 0.09 mg/kg and 0.26 mg/kg respectively were found to be the most enriched PTEs in soil, compared to their average continental crust concentrations (0.056 mg/kg and 0.102 mg/kg respectively). The levels of the evaluated PTEs in the study area are susceptible to increase over time if proactive steps are not taken to control mining and waste disposal activities.

Keywords

Environmental Pollution, Pollution Indices, Ecological Risk, Geo-Accumulation Index, Sediment Quality

1. Introduction

Environmental contamination by potentially toxic elements (PTEs) from mining activities is one of the most severe environmental issues in many parts of the world, due to their possible harm to human and environmental health (Reyes et al., 2020). Mining signifies the most detrimental environmental impacts as it involves the use of processing chemicals, the production of large amounts of waste, broad destruction of the landscape and removal of the vegetation (Candeias et al., 2011). Artisanal and small-scale gold mining (ASGM) in particular is linked to ideal introduction of PTEs into the environment (Nyanza et al., 2021) as a result of direct discharge of effluents and waste to surroundings with little to no pollution controls (Pavilonis et al., 2017; Gyamfi et al., 2019). These materials may contain various elements that, when discharged into the environment, accumulate in soil or get swept into water bodies. According to studies, over 99% of PTEs that enter water bodies end up in sediments, making them significant PTE sinks and repositories (Shen et al., 2019; Akoto & Anning, 2021). Elements such as As, Cd, Cr, Hg and Pb have detrimental effects on flora and fauna even in small amounts making them toxic at all concentrations (Dybowska et al., 2006).

The mobilization, distribution and concentration of PTEs in gold mining areas vary depending on geochemical characteristics of soil and tailings, but also mineralization of the particular environment (ur Rehman et al., 2020). The geochemistry of a mining area can thus be used to examine the type of hazardous contamination, potential risk to human and ecosystem health, and processes which dictate the concentrations and behaviors of PTEs in that area (Rivera-Parra et al., 2021).

Research on environmental geochemistry and pollution by PTEs in mining and mineral processing areas has been globally conducted extensively (Carrillo-Chávez et al., 2003; Basu et al., 2015; Boonsrang et al., 2018; Akoto & Anning, 2021; Haruna et al., 2021; Tang et al., 2021; Zhao et al., 2021; Olumayowa Oluwasola et al., 2023) although in some parts of the world such types of studies are not many. The studies demonstrate a connection between mining operations and PTEs-caused contamination, suggesting that mining plays a substantial role in environmental pollution (Akindele et al., 2023; Olumayowa Oluwasola et al., 2023). For example, Akindele et al. (2023) revealed that gold mining activities in the Osun River catchment area, a UNESCO World Heritage Site in Nigeria, resulted in PTEs contamination of benthic sediments, impaired water quality, and heavy metal bioaccumulation in macroinvertebrates.

For Tanzania where ASGM is characterized by labor-intensiveness with insufficient technical knowledge of mining and mineral processing; wide scattering of mine wastes and tailings to the environmental media and poor handling of mineral processing chemicals are some of typical outcomes (Dreschler, 2001). However, published information on environmental geochemistry of PTEs and their associated risk in small scale gold mines in Tanzania is scant despite the historic small-scale mining activities in the country. In fact, majority of the few studies

done in the country have mainly addressed issues of environmental pollution and degradation by trace elements, heavy metals or metalloids in large scale gold mines (Kitula, 2006; Bitala et al., 2009; Mganga et al., 2011; Åsgeir & Manoko, 2012; Mganga, 2014; Rwiza et al., 2016; Walwa, 2016) while others have focused on stratigraphy, rock alteration and petrogenesis (Vos et al., 2009; Kwelwa et al., 2013). However, studies that have been conducted in small scale mines have focused mainly on mercury (Hg) with little to no information on contamination by other PTEs (Taylor et al., 2005; Ikingura et al., 2006; Chibunda & Janssen, 2009; Spiegel, 2009; Bose-O'Reilly et al., 2010; Herman & Kihampa, 2015; Lema & Mseli, 2017). Nevertheless, the studies have not ascertained comprehensive information on the extent of pollution, geospatial distribution and environmental risk associated with PTEs in small-scale gold mining environments. These significant gaps impede initiatives for a thorough assessment of the environmental impacts and risks associated with artisanal and small-scale gold mining, not just in Tanzania but throughout sub-Saharan Africa. As such, lack of this crucial information results in reluctance when handling very toxic wastes and tailings resulting from mining activities.

Therefore, the present study assessed levels, geochemical distribution and environmental risk of five PTEs (As, Cd, Cr, Hg, and Pb) in an active small-scale gold mine in Nzega, Tanzania. Six (6) pollution indices were used for assessment of the level of contamination and environmental risk namely the enrichment factor (E_f), geo-accumulation index (I_{geo}), Pollution Load Index (PLI), Contamination Factor (C_f), degree of contamination (C_{deg}) and the Potential Ecological Risk Index (RI).

The results of this study are of utmost importance in determination of environmental implication of small-scale mining activities on subsequent environments for effective and evidence-based environmental management.

2. Materials and Methods

2.1. Study Area Description

Isanga mine is a Small-Scale gold mine situated within the area of the now closed and rehabilitated Resolute (Golden Pride) gold mine in Nzega district, Tabora region, Tanzania (**Figure 1**). It is located southeast of Lake Victoria, approximately 200 km south of Mwanza City and about 24 kilometers from Nzega town, within the Nzega greenstone belt, part of the Lake Victoria Gold Field (LVGF). Temperatures typically vary from 22˚C to 27˚C, and there is 700 to 800 mm of annual rainfall on average (Werema et al., 2016).

The Nzega greenstone belt is within the Nyanzian Super-group comprising of sedimentary rocks, subordinate mafic volcanics, Banded Iron Formations (BIF) and felsic volcanics (Nkya, 2013). Gold occurrence in the study area is normally associated with such rock formations with silica and chlorite ore types. Pyrite, arsenopyrite, pyrrhotite, and accessory minerals such as sulphosalts, galena, sphalerite, and Ni–Co–Bi sulphides are among the sulphide minerals found in

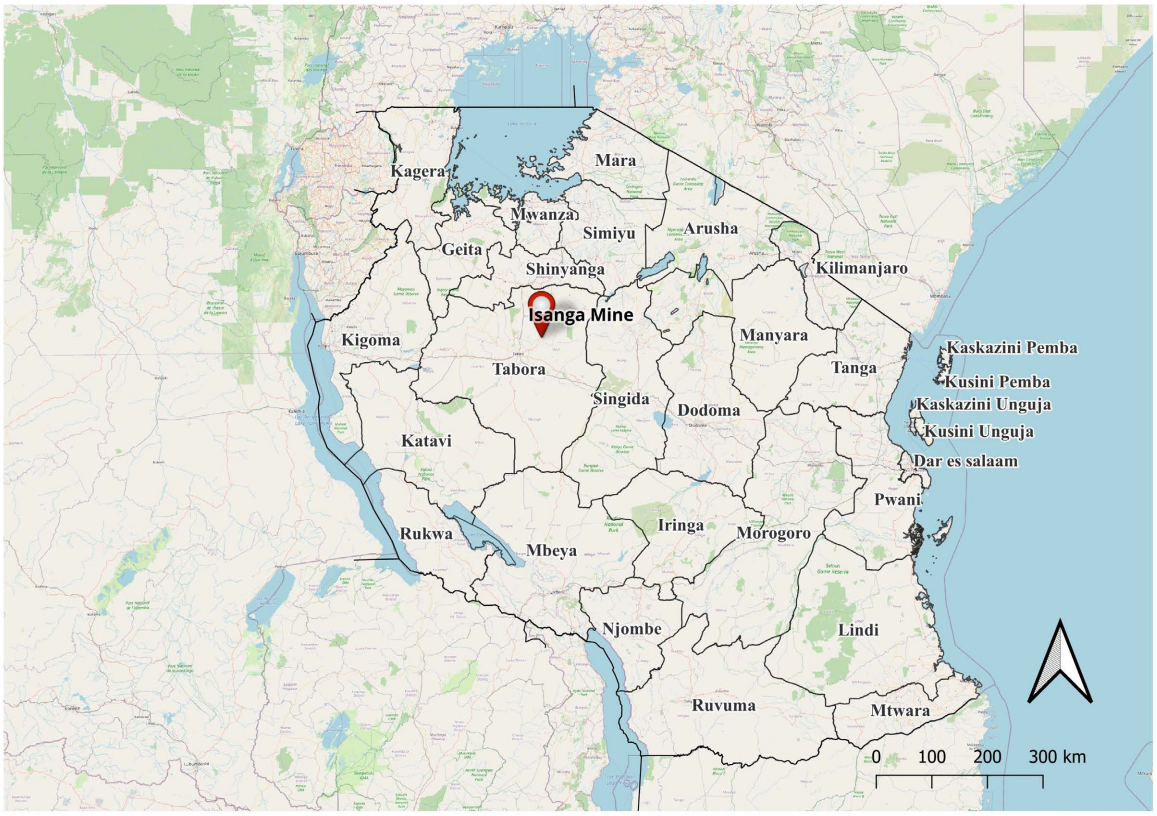

Figure 1. Map of Tanzania showing the location of Isanga Mine, in Nzega, Tabora.

both types of ore (Vos et al., 2009). The study area, easily accessible by road, contains both active and abandoned artisanal and small-scale gold mines.

The area has several rivers and seasonal streams crossing through. Some of these rivers and streams empty their water into Manonga River which is the largest river within the area and a distinguished source of water for communities around (**Figure 2(a)**). Other streams empty their water into closed Resolute (Golden Pride) mine pits which are main sources of water used in gold processing activities at the Isanga mine.

2.2. Sample Collection

A total of 16 soil and 20 sediment samples of about 500 g were gathered from the study area. Soil samples were collected within 0 - 20 cm depth of the top soil profile according to the US EPA guidance for environmental data collection (USEPA, 2002). Sediment samples were collected from areas with low flow in river channels, streams, processing areas and closed mine pits (pit lakes) within the study area. The samples were collected using a stainless scoop, placed into sealed and labelled plastic packages, transported and stored according to standard protocol (USEPA, 2001). For quality control purposes and avoiding cross-contamination of samples by digging equipment, digging devices were cleaned with deionized water after collection of each sample as done by Keith (2017). At each sampling location, a coordinate was taken for referencing purposes using a

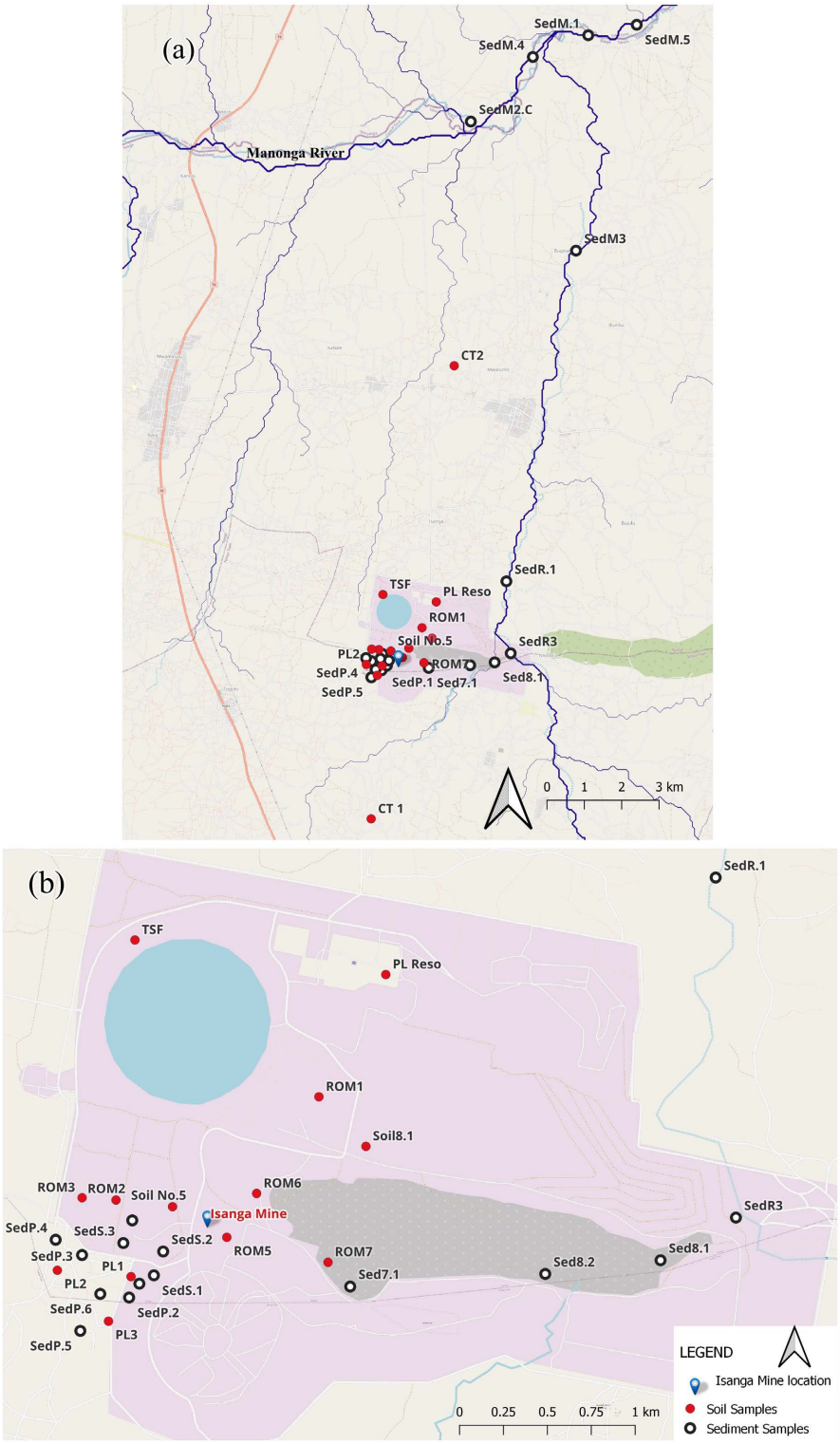

Figure 2. (a) A map showing soil and sediment sampling locations at the Isanga Mine and Manonga river. (b) A map showing soil and sediment sampling locations at the Isanga mine.

handheld GPS receiver (Garmin GPS MAP 64s). Sampling locations are indicated in Figure 2(a) and Figure 2(b).

2.3. Sample Preparation and Analysis

All sediment and soil samples were air dried, ground and sieved through 200 mesh screens. For determination of Cd, Pb, Fe and Cr, the soil and sediment samples were digested according to the standard digestion protocol (Method 3050B-SW-846) (USEPA, 1996). Methods 245.5 and 7062 (USEPA, 1994) were used during sample digestion for As and Hg analysis, respectively. As and Hg determination and their instrumentation protocols were performed as per standard guidelines (Baird et al., 2017). The atomic absorption spectrophotometer (AAS) Model WFX 210 was used to determine the concentration of PTEs from the digested samples. Hydride generation AAS (HG-AAS) was used for As and Hg analysis. AAS detection limits of As, Cd, Cr, Hg, Pb and Fe were 2 ppb (hydride), 0.1 ppm, 0.5 ppm, 2 ppb (hydride), 1 ppm and 0.5 ppm respectively. Three replicates assessed the analysis efficiency for each sample.

During soil and sediment digestion, representative dry weight homogeneous samples were treated in a series of steps. 10 g of each sample were digested by addition of 10 mg of conc. HNO_3 followed by 15 minutes of heating at 90˚C. The mixture was allowed to cool for sometimes followed by addition of 5 mL conc. HNO_3 and heated until no brown fumes. 2 mL of distilled water and 3 mL of H_2O_2 were added until no effervescence was observed. 10 mL of conc. HCl were added to the mixture and heated again for 15 min until approximately 5 mL remain of the sample. The digested samples were filtered using a filter paper (Whatman, No. 41) after which 5 mL of each sample were diluted to final volume of 100 mL using distilled water ready for analysis where respective hollow cathode lamps for the PTEs were applied accordingly. Concentrations of PTEs have been presented in mg/kg in this study.

2.4. Statistical and Geostatistical Data Analysis

Descriptive statistical analyzes including the Pearson Correlation Matrix (PCM) and Principal Component Analysis (PCA) were performed using Origin Pro 2022 statistical package (developed by OriginLab Corporation, Northampton, Massachusetts, USA). Pictographic illustration of level and spatial disparity of PTEs pollution were performed using QGIS version 3.28.2, an open-source geographic information system while Microsoft excel Version 2021 was used to compute geochemical pollution indices.

2.5. Sediment Quality Guidelines

Tanzania doesn't have national sediment quality guidelines (SQGs) for freshwater environments. However, the availability of approved SQGs by sediment-based toxicologists dealing with PTEs is a significant assistance for monitoring aquatic conditions, protecting aquatic biota, and establishing sound environmental policies concerning PTEs pollution (Rahman et al., 2022). SQGs were used in this study to assess the potential biotic impact of PTEs estimated in sediment samples taken from the study area. These SQGs included the threshold effect level

(TEL), probable effect level (PEL), effect range low (ERL), severe effect level (SEL), effect range medium (ERM), and lowest effect level (LEL) as compiled by Burton (2002).

2.6. Sediment and Soil Pollution Assessment

2.6.1. Geo-Accumulation Index (I_{geo})

The I_{geo} is a pollution index that indicates how natural geological processes and anthropogenic activities have influenced pollution by a given element (Muller, 1969; Abdullah et al., 2020; Napoletano et al., 2023). It is calculated using Equation (1):

$$I_{geo} = \log_2\left(\frac{Ci}{1.5 * Cb}\right) \tag{1}$$

where Ci denotes concentration of element i in soil and Cb is the geochemical background value of the element. 1.5 is a factor used to minimize likely variations in the background value of metal i due to lithological processes (Stoffers et al., 1986). The geochemical background values used in the present study are the Upper Continental Crust (UCC) averages proposed by Wedepohl (1995) which are 2, 35, 0.102, 17, and 0.056 for As, Cr, Cd, Pb, and Hg respectively. I_{geo} is classified as $I_{geo} < 0$ unpoluted; $0 \le I_{geo} < 1$ unpolluted to moderately polluted; $1 \le I_{geo} < 2$ moderately polluted; $2 \le I_{geo} < 3$ moderately to strongly polluted; $3 \le I_{geo} < 4$ strongly polluted; $4 \le I_{geo} < 5$ strongly to extremely polluted; and $I_{geo} \ge 5$ extremely polluted (Rabin et al., 2023).

2.6.2. Enrichment Factor (E_f)

E_f is used to determine possible anthropogenic source and degree of accumulation of heavy metals in sediments and soil in comparison with the typical occurrence of a given metal (Loska et al., 2005). It is calculated by making a metal with low occurrence variability and high chemical stability a reference element and using its concentration to estimate the E_f of the metal of interest (Barbieri, 2016). Fe and Al are mostly used as reference elements because their geochemical natures resemble many PTEs of environmental concern in both oxic and anoxic conditions (Rubio et al., 2000; Nowrouzi & Pourkhabbaz, 2014; Manna & Maiti, 2018). In the present study, Fe was used. Equation (2) is used for calculation of E_f:

$$E_f = \frac{(Ci/Cref)\text{sample}}{(Bi/Bref)\text{background}} \tag{2}$$

where Ci denotes measured concentration of PTE i; $Cref$ denotes concentration of a reference element; Bi is the background concentration of PTE i in soil (control); and $Bref$ is the background concentration of the reference element. The E_f values are categorized as follows: $E_f < 2$ shows deficiency to minimal enrichment; $2 \le E_f < 5$ purports moderate enrichment; $5 \le E_f < 20$ indicates significant enrichment; $20 \le E_f < 40$ indicates very high enrichment, and $E_f > 40$ indicates extremely high enrichment (Barbieri et al., 2015).

2.6.3. Contamination Factor (C_f) and Degree of Contamination (C_d)

C_f is an index that allows the assessment of soil contamination, by considering the present concentration of a given element in relation to the background value of the same element in soil or sediments. The degree of contamination (C_d) is then computed by summing up all factors of contamination of PTEs examined implying an inclusive pollution index of multi contaminants (Rutkowski et al., 2020). C_f is is calculated using Equation (3):

$$C_f = \frac{Ci}{Bi} \tag{3}$$

where Ci is the mean concentration of a given PTE in soil from at least five samples and Bi is the background concentration of that PTE in soil prior to mining activities. According to Justus Reymond & Sudalaimuthu (2023), contamination factors are classified as $C_f < 1$ (low factor of contamination); $1 \le C_f < 3$ (moderate factor of contamination); $3 \le C_f < 6$ (considerable factor of contamination); and $C_f > 6$ (very high factor of contamination) while degrees of contamination are categorized as $C_d < 6$ (low contamination degree); $6 \le C_d < 12$ (moderate contamination degree); $12 \le C_d < 24$ (considerable contamination degree) and $C_d > 24$ (high contamination degree)

2.6.4. Pollution Load Index (PLI)

PLI is used for assessment of the presence of soil pollution by a given PTE and determines the overall soil contamination degree (Sezgina et al., 2019). This index makes available a means to demonstrate the alteration of soil conditions due to increase in the amount of PTEs within that soil (Kowalska et al., 2018). The PLI is calculated based on Equation (4):

$$\text{PLI} = \sqrt[n]{CF_1 \times CF_2 CF_3 \times \cdots \times CF_n} \tag{4}$$

where n is the number of analyzed PTEs in soil, CF_n is a computed factor of contamination of PTE n. PLI values were classified into two classes where a value of PLI < 1 implies unpolluted while PLI > 1 implies pollution. The values of PLI > 1 are further classified by Sezgina et al. (2019) as follows: (1 < PLI ≤ 2) represents low to moderate pollution; (2 < PLI ≤ 3) represents moderate pollution; (3 < PLI ≤ 4) represents moderate to severe pollution; (4 < PLI ≤ 5) represents severe pollution; and (PLI > 5) represents very severe pollution (Sezgina et al., 2019).

2.6.5. Potential Environmental Risk Index (PERI)

The PERI of PTEs is a useful index for assessment of the extent of ecological risk caused by concentrations of PTEs in environmental media (Romzaykina et al., 2021). It is estimated by computing the overall potential ecological risk index (PERI) (Romzaykina et al., 2021) using Equation (5):

$$\text{PERI} = \sum_{i=1}^{n} E_i \tag{5}$$

$E_i = T_i \times CF_i$, where, n is the number of PTEs being accessed; E_i is a risk factor of PTE i function of the contamination factor; T_i is a factor for toxic response on

the assessed PTE. T_i values used for Hg, Cd, As, Cu, Ni, Pb, Cr and Zn are 40, 30, 10, 5, 6, 5, 2, and 1 respectively (Hakanson, 1980; Kumar et al., 2021). Romzaykina et al. (2021) classified E_i values as $E_i < 40$—low ecological risk, $40 \le E_i < 80$—moderate ecological risk, $80 \le E_i < 160$—considerable ecological risk, $160 \le E_i < 320$—high ecological risk, $E_i \ge 320$—very high ecological risk. The PERI was classified as follows: PERI < 150—low ecological risk, 150 ≤ PERI < 300—moderate ecological risk, 300 ≤ PERI < 600—considerable ecological risk, PERI ≥ 600—very high ecological risk (Hakanson, 1980; Romzaykina et al., 2021).

3. Results and Discussion

3.1. PTEs Concentration in Sediments and Soil

The minimum, maximum, mean and standard deviation concentrations of five PTEs (As, Hg, Pb, Cd and Cr) in 20 sediment and 16 soil samples collected within the study area (Isanga gold mine and vicinities) are summarized in **Table 1**. The concentrations of PTEs in both sediment and soil matrices were in the following order: Cr > Pb > Cd > As > Hg, and the ranges of their concentrations (mg/kg) in both sediment and soil samples are presented in **Table 1**.

Hg and Cd mean concentrations in soil were above the average concentrations in the upper continental crust (0.056 mg/kg and 0.102 mg/kg respectively) as estimated by Wedepohl (1995). The results were also compared to PTE concentrations in control samples collected about 6 kilometers from the mining area in order to better understand the relationship between the lithology of the surrounding environment and the level of contamination in the study area. The

Table 1. Concentrations of PTEs in samples of soil and sediments collected from the Isanga mine and its vicinities.

		PARAMETERS (mg/kg), dry weight basis					
		As	Pb	Cd	Hg	Cr	Fe
Soil Samples (n = 16)	Mean	0.40	3.96	0.26	0.09	27.45	574.03
	Standard Deviation	0.20	1.66	0.07	0.07	0.18	141.07
	Median	0.365	4.015	0.24	0.085	27.445	592.2
	Minimum	0.11	0.99	0.15	0	27.11	336.91
	Maximum	0.87	6.67	0.38	0.22	27.79	803.58
	UCC[a]	2	17	0.102	0.056	35	483.17
Sediment samples (n = 20)	Mean	0.38	4.58	0.27	0.14	27.51	522.434
	SD	0.231	1.48	0.12	0.11	0.20	103.559
	Median	0.315	4.585	0.27	0.125	27.55	510.9
	Minimum	0.02	1.64	0.03	0	27.18	373.08
	Maximum	0.85	7.6	0.48	0.41	27.83	736.85
	Background[b]	0.31	4.87	0.09	0	27.41	417.86

[a]UCC = Upper continental crust background concentrations as per Wedepohl (1995); [b]Background values from the control sample.

comparison revealed that, with the exception of Cd, which had a mean concentration of 27.45 mg/kg as compared to the control (27.585 mg/kg), all the analyzed PTEs had average concentrations that were slightly above background levels in control samples. Such results can be linked to the impact of mining operations in the study area as proposed in a similar study by Zhao et al. (2021). The higher concentrations of Hg as compared to its average concentration in the continental crust and in the control samples than other heavy metals, can be linked to Hg use in gold amalgamation processes in the study area.

Similarly, the mean concentrations of all the assessed PTEs in sediments were above concentrations of the same in the control sample collected from upstream of Manonga river about 9 km from the Isanga mine. These findings suggest that there was a slight degree of pollution in the mining area in both soil and sediment matrices. The slight difference of concentration of other PTEs in relation to their concentration in control samples is most likely related to less discharge to the environment.

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Fe, which was analyzed to serve as a reference element in the enrichment factor computation (Barbieri et al., 2015), was found to be slightly higher in both soil and sediment samples. Fe was found to have an average concentration of 574.03 mg/kg in soil, higher than the background value of 483.17 mg/kg for the upper continental crust, and 522.434 mg/kg in sediments, higher than the background concentration of 417.86 mg/kg. Such elevated Fe concentrations can be linked to the existence of Banded Iron Formations (BIF) as well as pyrite, arsenopyrite, and pyrrhotite mineralization in gold-bearing rocks in the studied

area (Vos et al., 2009; Nkya, 2013).

3.2. Sediment Quality

For the purpose of assessing the potential biotic impact of PTEs estimated in sediment samples, the comparison between average concentrations and different SQGs is shown in Table 2. The SQGs in Table 2 indicated that the sediments contained acceptable concentrations of As, Pb, Cd, and Hg below threshold biotic impact. However, with regard to the LEL and SEL guidelines, Cr concentration (27.51 mg/kg) was above threshold biotic effect (26 mg/kg) and above extreme biotic effect (10 mg/kg). These findings suggest that PTEs, particularly Cr, have contaminated the sediments that were collected from various riverine systems, ore washing bays, and water swamps within the study area and have a potential to cause biotic impacts.

It should however be noted that, in determining whether or not sediments are harmful or have been polluted by PTEs, SQGs exhibit different percentages of false positive and false negative outcomes. When a PTE concentration in a sediment surpasses a SQG that indicates it is dangerous when it is not, this is known as a false positive. The reverse is a false negative, where the concentration of a PTE in the sediment is below the SQG and purports to be nontoxic but is harmful to aquatic biota under normal circumstances (Burton, 2002).

3.3. Pollution Source Apportionment and Elemental Composition Relationships

3.3.1. Pearson's Correlation Analysis of PTEs

The Pearson Correlation Matrix (PCM) is a multivariate analysis method used to determine the potential sources of PTEs and determine the extent of their quantitative relationships (Zhao et al., 2021). PTEs having a shared geochemical history or origin may exhibit strong correlations with one another. Table 3 shows PCM results for PTEs in soil and sediments collected from the Isanga mine and its vicinities. A moderate positive correlation was observed for As – Hg in soil (r

Table 2. Concentrations of PTEs in sediments compared to different sediment quality guidelines for metals (in mg/kg).

	As	Pb	Cd	Hg	Cr	Effect Level
PTEs' Mean Concentration	0.38	4.58	0.27	0.14	27.51	
TEL[a]	5.9	35	0.6	0.17	37.3	Threshold
ERL[a]	33	35	5	0.15	80	
LEL[a]	6	31	6	0.2	26	
PEL[a]	17	91.3	3.53	0.486	90	Midrange
ERM[a]	85	110	9	1.3	145	
SEL[a]	33	250	10	2	10	Extreme

[a]Values for SQGs adopted from Burton (2002); [a]Abbreviations defined in Section 2.5.

Table 3. Pearson correlation matrix for PTEs concentrations in soils and sediments.

		Pearson Correlation					
	Elements	**As**	**Pb**	**Cd**	**Hg**	**Cr**	**Fe**
Soil Samples	**As**	1					
	Pb	0.471	1				
	Cd	0.460	0.370	1			
	Hg	0.686*	0.488	0.173	1		
	Cr	−0.019	0.435	0.229	−0.233	1	
	Fe	−0.234	0.079	−0.004	−0.077	−0.222	1
Sediment Samples	**As**	1					
	Pb	0.084	1				
	Cd	0.177	−0.181	1			
	Hg	−0.045	−0.400	0.552**	1		
	Cr	−0.176	0.083	0.223	0.051	1	
	Fe	−0.294	−0.013	0.194	0.361	0.246	1

*Correlation is significant at $p < 0.01$ (2-tailed); **correlation is significant at $p < 0.05$ (2-tailed).

= 0.686, $p < 0.01$) and Cd – Hg in sediments (r = 0.552, $p < 0.05$) indicating that Hg may have similar sources, similar geochemical processes or similar pathways with As in soils and Cd in sediments within the Isanga mine and its nearby environment. The Hg – Cd correlation in sediments may also indicate that Hg and Cd behaved similarly during deposition into sediments (Nkinda et al., 2021; Tang et al., 2021). There was also a notable but not significant positive correlation for As – Pb (r = 0.471, $p > 0.05$), As – Cd (r = 0.460, $p > 0.05$), and Pb – Hg (r = 0.488, $p > 0.05$) suggesting a similarity in input sources for As, Pb, Cd and Hg in soil.

3.3.2. Principal Component Analysis (PCA)

Figure 3(a) and **Figure 3(b)** show PCA biplots for soil and sediment samples respectively. The PCA was used to determine the relationship and variations of soil and sediment datasets and explain possible sources of PTEs by computing the eigenvectors and determining the major components. The eigenvalues and extracted eigenvectors (PC1 and PC2) for both soils and sediments are presented in **Table 4**.

Using the Kaiser criterion, PTEs with eigenvalues greater than 1 are selected as principal components in this study. For soil samples, values in **Table 4** with eigenvalues greater than one accounted for 80.91% of the cumulative variance. PC1 had a strong positive correlation with As (0.558), Pb (0.505), Hg (0.482) and Cd (0.404) whereas PC2 had strong positive correlation with Cr (0.784) and a negative correlation with Hg (−0.457) (**Table 4** and **Figure 3(a)**). PC1 was, to a larger extent, loaded with As that explained 39.92% of the total variance, while PC2 was highly loaded with Pb that explained 22.97% of the total variance.

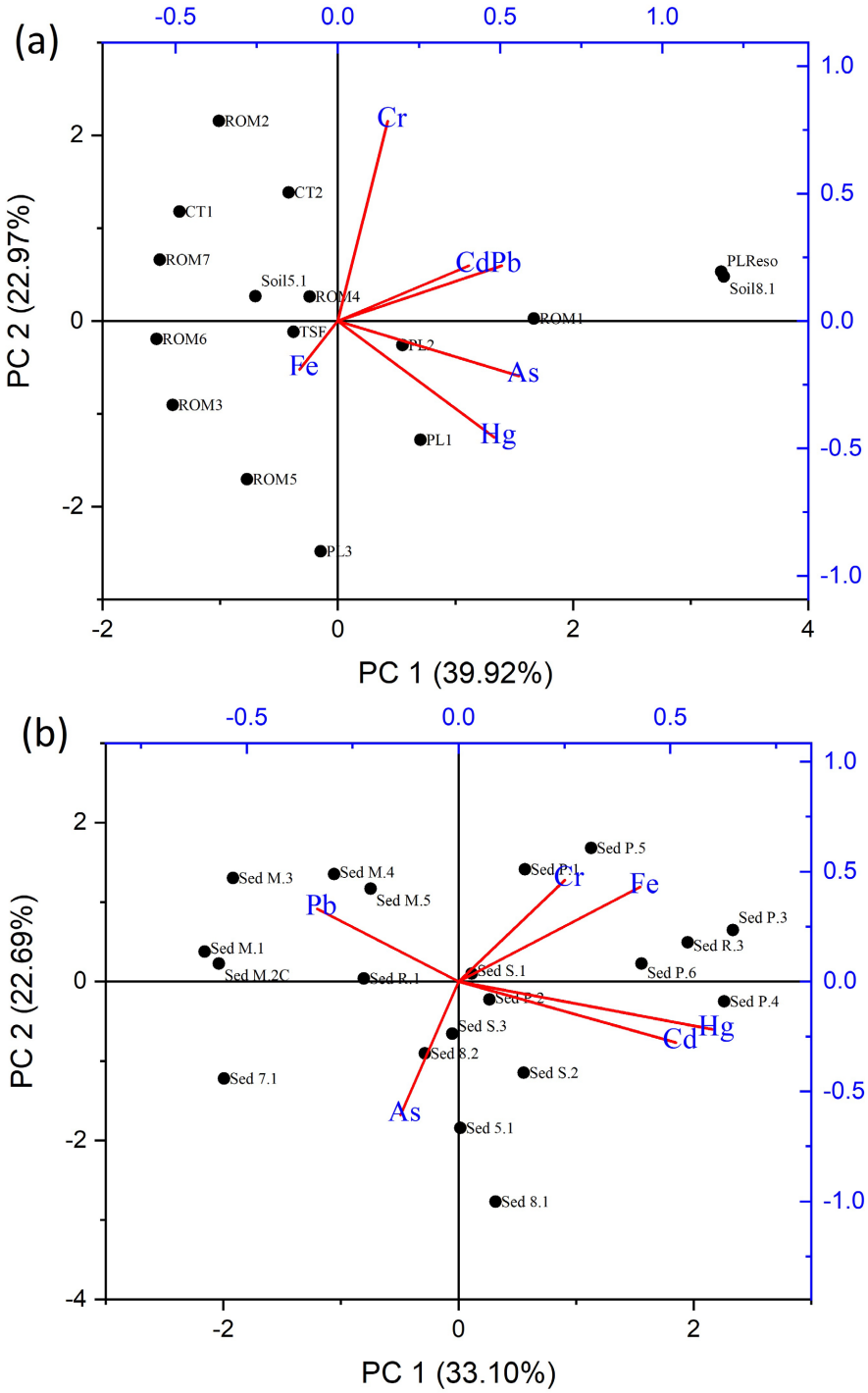

Figure 3. PCA biplots of PTEs in soils from Isanga gold mine for soil (a) and for sediments (b).

Similarly for sediment samples, PC1 was highly loaded with As that explained 33.10% of the total variance while PC2 was loaded with Pb that explained 22.69% of the overall variations. PC1 and PC2 with eigenvalues greater than 1 for sediment samples accounted for 73.88% of the cumulative variance. PC1 of sediment samples had a strong positive correlation with Hg (0.600) and Cd (0.514), whereas

Table 4. Eigenvalues and PCA analysis results of PTEs in soil and sediments.

	Element	Eigenvalue	Percentage of Variance (%)	Cumulative (%)	PC1	PC2
Soil	As	2.395	39.92	39.92	0.558	−0.216
	Pb	1.378	22.97	62.89	0.505	0.217
	Cd	1.081	18.02	80.91	0.404	0.217
	Hg	0.745	12.41	93.32	0.482	−0.457
	Cr	0.237	3.94	97.27	0.154	0.784
	Fe	0.164	2.73	100.00	−0.117	−0.190
Sediment	As	1.986	33.10	33.10	−0.137	−0.607
	Pb	1.362	22.69	55.79	−0.334	0.331
	Cd	1.086	18.09	73.88	0.514	−0.278
	Hg	0.754	12.56	86.45	0.600	−0.218
	Cr	0.488	8.13	94.57	0.251	0.462
	Fe	0.326	5.43	100.00	0.429	0.430

PC2 had strong negative correlation with As (−0.607) and a positive correlation with Cr (0.462) (**Table 4** and **Figure 3(b)**).

From these results, it is possible to conclude that Cr, As, Pb and Hg concentrations in soil as well as Hg, Cd and Cr concentrations in sediments could be associated with gold processing activities (Tang et al., 2021) especially irresponsible storage and management of tailings, process effluent waters and waste rock in the study area. The negative correlation of Hg in soil can also be related to a source different from other PTEs which may be its use in gold amalgamation activities. As in sediments may have a different loading mechanism compared to other PTEs.

3.4. Pollution Assessment of PTEs in Soil and Sediments

Based on the average concentrations of PTEs in the continental crust as estimated by Wedepohl (1995) and the background concentration of PTEs in sediments derived from the control sample collected upstream of the Manonga river, several pollution indices for soil and sediments respectively were computed. The indices are the I_{geo}, E_f, C_f, Cd, PLI and PERI as indicated in **Table 5**.

The I_{geo} for the assessed PTEs was in order Cd > Hg > Fe > Cr > Pb > As for soil and Cd > Fe > As > Cr > Pb > Hg for sediments. The I_{geo} was less than 0 for As, Pb, and Cr in both surface soils and sediments indicating no pollution by these PTEs. Although the I_{geo} was less than 0 for Hg in sediments indicating no pollution, it was 0.019 for soil indicating slight pollution of soil by Hg. The I_{geo} for Cd was greater than zero (0.749 for soil and 0.968 for sediments), indicating no to moderate Cd pollution in both soil and sediments. All of the examined PTEs showed an E_f less than 2, suggesting depletion to little anthropogenic enrichment, with the exception of Cd, whose E_f was slightly above 2 in both soil

Table 5. Computed pollution indices in soil and sediments.

Geochemical index	Compartment	As	Pb	Cd	Hg	Cr	Fe
Geo Accumulation Index	Soil	−2.891	−2.687	0.749	0.019	−0.936	−0.336
	Sediment	−0.291	−0.674	0.968	−2.856	−0.579	−0.263
Enrichment Factor	Soil	0.170	0.196	2.121	1.279	0.660	1.000
	Sediment	0.980	0.752	2.347	0.138	0.803	1.000
Contamination Factor	Soil	0.202	0.233	2.520	1.520	0.784	1.188
	Sediment	1.226	0.940	2.935	0.138	1.004	1.250
Risk Factor	Soil	2.022	1.165	75.607	60.804	1.569	1.188
	Sediment	12.258	4.702	88.038	5.524	2.008	1.250
Degree of contamination	Soil	6.448					
	Sediment	7.493					
PLI	Soil	0.743					
	Sediment	0.915					
PERI	Soil	142.353					
	Sediment	113.781					

and sediments (2.121 for soil and 2.347 for sediment), indicating moderate anthropogenic enrichment of the PTE. In contrast to As and Cr, which both had contamination factors in soil below one (0.202 and 0.784, respectively), Hg had a contamination factor below one (0.138) in sediments, indicating a low contamination factor, and above one (1.520) in soil, indicating a moderate contamination factor. Cd had soil and sediments contamination factors above 1 that were moderate (2.520 and 2.935, respectively), while Pb showed low contamination factors of 0.233 and 0.940 in soil and sediments respectively. The contamination degree of the study area was 6.448 for soil and 7.493 for sediments, indicating a low soil contamination degree and a moderate sediment contamination degree.

Aside from Cd and Hg, all other PTEs tested had an $E_i < 40$, indicating a low ecological risk in both soil and sediments. Cd had an E_i of 75.607 for soil, suggesting a moderate ecological risk, and an E_i of 88.038 for sediments, indicating a significant ecological risk. Hg posed a moderate ecological danger in soil (E_i = 60.804) but a low ecological risk in sediments (E_i = 5.524). Although Hg had a low ecological risk in sediments, it had high concentrations of up to 0.41 mg/kg in samples obtained from amalgamation bays, which is greater than threshold concentrations set in the TEL, ERL, and LEL sediment quality guidelines (0.17, 0.15, and 0.2 mg/kg, respectively) implying that it can induce biotic impacts. The PLI values for both soil and sediments were less than 1, indicating that the site is not considerably polluted by the assessed PTEs. The PERI was less than 150 (142.353 for soil and 113.78 for sediments), indicating that the study area poses little ecological risk.

4. Conclusions and Recommendations

The present study investigated the extent of PTEs pollution for Cr, Cd, Pb, Hg, and As in soils and stream sediments of the Isanga small scale gold mine situated in the area of the now closed and remediated Resolute gold mine, in Nzega, Tanzania. Hg concentrations in the study area were higher than average concentrations in the continental crust and control samples, implying that such pollution may be caused by Hg use and disposal practices during gold amalgamation processes.

The soil contamination in the study area was low, and the sediment contamination was moderate. Cd was identified as a significant contaminant in both the soil and sediment compartments, with contamination factors of 2.520 and 2.935, respectively. Except for Cd, which showed moderate enrichment and was most likely derived from mining activities, the other PTEs in soil and sediments had no significant anthropogenic enrichment. Despite the moderate enrichment of Cd in both soil and sediments, as well as the moderate degree of sediment contamination in the study area, the PTEs in the study area were found to have a low potential to cause ecological risks. However, if proactive measures are not taken to control mining and waste disposal operations, the levels of the assessed PTEs in the study area will certainly continue to rise over time and finally result in a high ecological risk.

The current study suggests that proper run-of-mine and mine water and waste management controls should be implemented to reduce environmental pollution caused by PTEs. Mine waste management plans that allow for the management of wastes and tailings in a linear fashion from production to disposal, the construction of lined tailing storage facilities suitable for small scale mining operations, and eventually in situ closure of mines or waste storage facilities, could be the most effective controls as per the observations made in this study. Additionally, a routine environmental audit of the mine environment is necessary to make sure that conducts that cause pollution are avoided and under control. Small-scale gold miners in Tanzania are characterized by inadequate technical knowledge of mining and mineral processing operations and improper waste management controls. Therefore, the government should step up routine sensitization and awareness raising initiatives on mine water and mine waste management in small scale mining operations.

This study successfully demonstrated that multivariate statistical approaches such as Pearson's Correlation and Principal Component analyses of geochemical data are useful and effective techniques for determining elemental composition relationships in both soil and sediment compartments. Such statistical tools enable the identification and prediction of likely causes and sources of pollution in a specific area. However, the study didn't apportion the exact origins of PTEs identified to have the potential to cause ecological risks in the study area. Such apportionment was out of scope of this study, but future research may take it into account and broaden the study's coverage of the Lake Victoria Greenstone

Belt, which is known to be home to hundreds of small-scale gold mining operations.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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