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Health risks associated with heavy metal pollution of soils in communities surrounding an abandoned mine tailings dam

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Abstract

The encroachment of mine tailing dams threatens residents' health due to heavy metals in tailings. The study assesses the extent of heavy metal (Fe, Mn, Cu, Zn, As, Cd, and Pb) contamination and potential health risks of communities sited near the Pompora tailing dam. Soil samples from eight (8) communities were examined for the presence of heavy metals, and the extent of contamination was estimated using the contamination factor (CF), pollution load index (PLI), geo-accumulation index (I-geo), and enrichment factor (EF). The hazard quotient and hazard index were calculated to predict the potential adverse effects of heavy metals via ingestion in children, adult females, and males. The concentrations of Fe (24,464.75–46,751.0 mg/kg), Mn (2,269.75–4,911.0 mg/kg), As (55.4–90.93 mg/kg), and Pb (70.58–91.38 mg/kg) were above the world average, sub-regional levels, and most reports within the Obuasi Municipality. The PLI indicated significant heavy metal pollution (PLI > 1) in all communities near the Pompora tailing dam. In contrast, the contamination factor indicated very high contamination (CF > 6) for Mn, Cd, and As, with the I-geo indicating strong As pollution. The hazard quotient and index unveiled potential adverse health effects in children accruing from As pollution in soil via ingestion, with communities closer to mine installations being most impacted. The study reveals heavy metal pollution in the soil of communities near the Pompora tailing dam, with As pollution posing potential health risks in children, consequently necessitating ecologically friendly intervention to safeguard public health.

Keywords
Mine tailing dam, heavy metals, health risk, pollution

Introduction

The global demand for gold has increased mineralogycal explorations, resulting in more tailing dams to store wastes (tailings) (Araujo et al., 2022; Azam & Li, 2010; Guimarães et al., 2023; Owen et al., 2020). Mine tailings constitute a global conundrum due to their complex composition, which requires diverse techniques for decontamination (Araujo et al., 2022; Huang et al., 2012; Islam & Murakami, 2021; Jayapal et al., 2023; Kaninga et al., 2020). Reports indicate that gold mining has replaced cocoa as Ghana's highest foreign exchange earner, stemming from the ever-increasing spate of mining explorations, with a concomitant increase in tailing dams and abandoned mine pits (Kazapoe et al., 2022; Kumi et al., 2024; Mensah & Addai, 2024). Although mining companies adopt phytoremediation after the stabilization of tailings, many dams are abandoned after a decade, leading to failures, underground and surface water pollution, and soil pollution (Amoakwah et al., 2020; Azizi et al., 2022; Gyamfi et al., 2019; Nkansah & Belford, 2017; Petelka et al., 2019). Heavy metals such as cadmium,

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arsenic, lead, zinc, copper, manganese, and iron are relatively non-biodegradable, persist in biological systems, and are highly toxic at low concentrations (Antoniadis et al., 2019; Bharti & Sharma, 2021; Fural et al., 2020; Fu & Xi, 2020; Ojuederie & Babalola, 2017). The prevalence of malaria, organ failure, and cancer associated with settlement encroachments close to tailing dams is not uncommon in mining towns, and the Pompora tailing dam, located near the central district of the Obuasi municipality, is no exception (Baah-Ennumh & Adom-Asamoah, 2019; Kwaning & Atteh, 2022; Mensah et al., 2015). Assessing the extent of heavy metal pollution could be complicated; nonetheless, the contamination factor, pollution load index, and geo-accumulation index provide an unbiased evaluation of the state of heavy metal pollution, with the hazard index and quotient communicating their associated potential health ramifications (Chen et al., 2022; Khan et al., 2021; Krasavtseva et al., 2021; Rai et al., 2019). Studies carried out within the Obuasi municipality have mostly focused on As contamination in surface soil without providing a broader scope of heavy metal contamination assessment (Amonoo-Neizer et al., 1996; Antwi-Agyei et al., 2009; Banson et al., 2020; Bempah et al., 2013; Osei Akoto et al., 2018). Moreover, these studies do not include health risks associated with the heavy metals in surface soil, thus limiting the possible intervention. Consequently, the extent of heavy metal pollution in communities in the environs of the Pompora tailing dam remains unknown. Therefore, this study examines the extent of heavy metal pollution in the surface soil of communities, the potential sources and relationship between metals, and their associated health risks in communities within the catchment area of the Pompora tailing dam.

Materials and Methods

Study area and sampling

The Pompora tailings dam is located at Obuasi in the Ashanti Region of Ghana with coordinates 6°13'11" – 6°13'19" N and 1°39'25" – 1°38'24" W (Figure 1). The landform is undulating and above 500 m and falls within the Ashanti belt of the Pre-Cambrian and Birimian formations noted for their rich gold ore body. The soil type is forest ochrosol situated within Ghana's tropical rainforest zone with annual average precipitation of 142 mm and a mean temperature of 26 °C. Obuasi experiences high humidity (75 – 85 %), especially during the rainy season, which spans April – September. Sampling was conducted in the dry season (December – March) in eight settlements within a 1 km range of the Pompora tailings dam catchment area (Figure 1). Samples were collected 10 – 15 cm from the topsoil in four replicates into sterile zip-locked bags and placed on ice before transporttation to the laboratory, where it was kept frozen (-4 °C) before drying.

Digestion and heavy metal determination

Soil samples were dried in an oven at 60 °C until a uniform weight was obtained and sifted through a 2 mm sieve. Replicate samples were made ready for heavy metal analysis after acid digestion using the US EPA Method 3050B with modifications. One gram (1 g) of soil samples was introduced into Khedjahl tubes and digested with an acid mixture of perchloric, nitric, and hydrochloric acids (1:2:3 v/v). The mixture was swirled gently on hot plate (100 °C) to complete the digestion. The concentrations of heavy metals in soil samples were measured using the Buck Scientific 210 VGP at the following wavelengths: As at 193.7 nm, Cu at 324.8 nm, Cd at 228.3 nm, Fe at 248.3 nm, Pb at 217 nm, Mn at 279.5 nm and Zn at 213.9 nm.

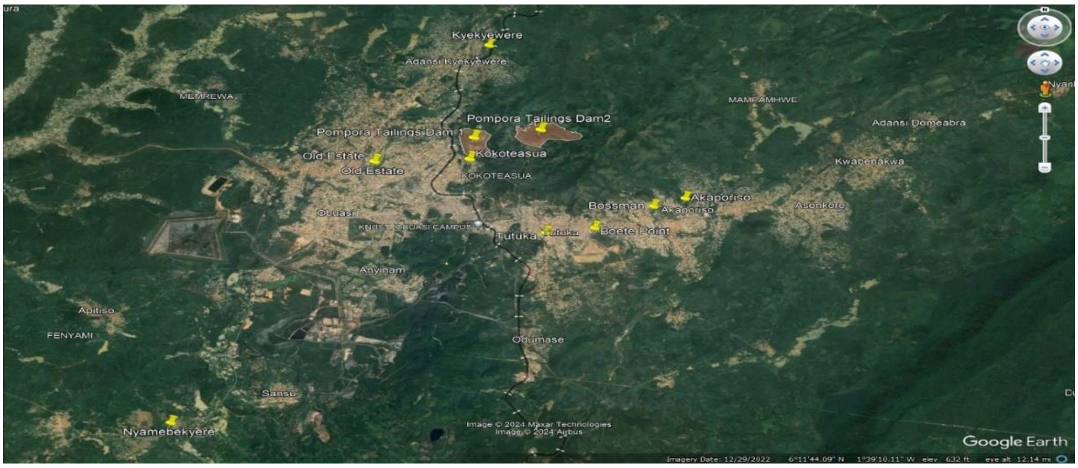

Figure 1
Image of the study area showing sampling points and the Pompora tailings dam

Data, multivariate analyses and pollution assessment

Analysis of variance (ANOVA) of heavy metals in soil was conducted using the Tukey-b multiple compareson test in Statistical Package for Social Sciences (version 20). Pearson correlation explored the relationships between different heavy metals in soil, while principal component analysis determined the main contributing factors underlying heavy metal pollution of soils in communities surrounding the Pompora tailings dams. Graphs for the hazard index and pollution load index were plotted in Origin Pro (version 2020).

Assessment of heavy metal pollution. The contamination factor of heavy metals in the soils of communities surrounding the Pompora tailings dam was estimated using the following formula [1]:

$$\text{Contamination factor (Cf)} = \text{Mx} / \text{Mb} \qquad [1]$$

where Mx represents the concentration of heavy metals in soil, and Mb represents the background concentrations of heavy metals on the worldwide average in soil (Kabatas-Pendias, 2011). Reference values (mg/kg) are as follows: Fe (20,000), Mn (488), Cu (38.5), Zn (70), As (6.8), Cd (0.2) and Pb (27). The contamination factor was categorized using the following criteria: Low contamination ($Cf < 1$), moderate contamination ($1 \leq Cf < 3$), considerable contamination ($3 \leq Cf < 6$), and very high contamination ($Cf \geq 6$) (Abrahim & Parker, 2008; Li et al., 2015; Mensah et al., 2021).

The pollution load index (PLI) integrates all the contamination factors and assesses the extent of contamination for a sampling site (Angulo, 1996; Rinklebe et al., 2019; Yahaya et al., 2021). The pollution load index was calculated using the following formula [2]:

$$\text{Pollution load index (PLI)} = (Cf_1 \times Cf_2 \ldots Cf_n)^{1/n} \qquad [2]$$

where Cf_1, Cf_2, and *n* are contamination factors for heavy metals 1, 2, and n number of heavy metals respectively. The pollution load index is regarded as significant if it is greater than one or unity ($PLI > 1$), whereas $PLI < 1$ is regarded as insignificant (Weissmannová et al., 2019).

The geo-accumulation index (I-geo) determines heavy metal pollution in soil (Müller, 1969). This index compares the extent of contamination in the soil to geochemical background levels; thus, it is used to decipher the extent of anthropogenic contribution to heavy metal pollution (Soleimani et al., 2023; Tume et al., 2022). The following formula was used to calculate the geo-accumulation index, and Müller (1969) proposed seven classes for the classification of the geo-accumulation index (Table 1)

$$\text{I-geo} = \log_2 (\text{Cn} / 1.5\text{Bn}) \qquad [3]$$

where Cn refers to the concentration of heavy metal in soil, Bn refers to the heavy metal's geochemical background concentration, and 1.5 is a factor introduced to reduce the effect of potential variations in geochemical background values.

Table 1. *Classification of geo-accumulation index*

I-geo value	Category	Description
> 5	6	Extreme contamination
4 – 5	5	Strong to extreme contamination
3 – 4	4	Strong contamination
2 – 3	3	Moderate to strong contamination
1 – 2	2	Moderate contamination
0 – 1	1	Uncontaminated to moderate contamination
0	0	Uncontaminated

The enrichment factor compares the levels of heavy metals in soil to uncontaminated background levels, thereby estimating the extent of anthropogenic impact on soil quality (Agyeman et al., 2023; Darko et al., 2017) (Table 2). The enrichment factor (EF) uses Fe or Al levels in the soil as normalizing elements based on the assumption that their presence in the soil is due to geogenic sources (Abrahim & Parker, 2008; Li et al., 2015; S. M. Shaheen et al., 2020). Thus, the following formula was used to calculate the enrichment factor of heavy metals in soil:

$$\text{EF} = (\text{Cs} \times \text{Fn}) / (\text{Cn} \times \text{Fs}) \qquad [4]$$

where Cs and Cn represent heavy metal concentration in soil and uncontaminated background samples, Fs and Fn represent the concentration of Fe in soil and Fe in continental shale, respectively (Turekian & Wedepohl, 1961). The following shale concentrations were applied as background values to

Table 2. *Classification of the enrichment factor*

Enrichment factor value	Classification of Contamination (Azizi et al., 2022)	Source attribution (Li et al., 2015)
EF< 1	No enrichment	EF = 0.5 - 1.5 (Natural origin)
EF= 1 – 3	Minor enrichment	
EF= 3 – 5	Moderate enrichment	EF > 1.5 (Anthropogenic origin)
EF= 5 – 10	Severe enrichment	
EF > 10	Very severe enrichment	

calculate the enrichment factor (As = 2, Cd = 0.1, Cu = 14.3, Fe = 30,890, Mn = 527, Pb = 17, Zn = 52) (Wedepohl, 1995).

Health risk assessments

The non-carcinogenic risk arising from ingesting soils containing heavy metals was estimated using the US-EPA (1986) health risk assessment model. The average daily dose in children, adult females and males (mg/kg day) via the oral route was calculated as follows:

$$ADD_{ingestion}=C\times([IR\times EF\times ED]\times 10^{-6})/(BW\times AT) \quad [5]$$

where $ADD_{ingestion}$ refers to the average daily dose of ingested heavy metal, the concentration of heavy metals in soil, C; ingestion rate, IR (200 mg/day; children, 100 mg/day; adult female and male), exposure frequency, EF (350 days/year; children, 250 days/year; adult female and male), exposure duration, ED (6 years; children, 25 years; adult female and male); bodyweight, BW (15 kg; children, 68 kg; adult male, and 58; adult female); averaging time, AT (2190 days; children, 9125 days; adult female and male); unit conversion is 1×10^{-6} (Li et al., 2015; Mensah & Addai, 2024; Parlak et al., 2022; Penteado et al., 2021).

The hazard quotients of heavy metals were also estimated as follows:

$$HQ = ADD / RD \quad [6]$$

where average daily dose of heavy metal, ADD; reference dose of heavy metal, RD (mg/kg day) given as follows: lead (0.0035); zinc (0.3); cadmium (0.001); iron (0.7); manganese (0.046), copper (0.04) and arsenic (0.0003) as indicated in earlier reports (Antoniadis et al., 2019; Chen et al., 2022; Darko et al., 2017; Rinklebe et al., 2019). The hazard index, which is the sum of hazard quotients for heavy metals in the soil, was calculated using the following formula [7]:

$$HI = \sum HQ \quad [7]$$

The possibility of adverse impacts is minimal when the hazard quotient (HQ) or hazard index is less or equal to unity. Conversely, the possibility for adverse effects to occur is high when HQ or HI is greater than unity (HQ, HI > 1) (Li et al., 2015).

Results and Discussion

Levels of heavy metals in soil

The concentrations of heavy metals in the soils of communities surrounding the Pompora mine tailings dam are presented in Table 3. The concentrations of Fe in soil were higher than the other heavy metals studied and ranged between 24,464.75 mg/kg - 46,751.00 mg/kg. Thus, the concentrations of Fe in communities such as Kyekyewere and Nyamebekyere were two - fold greater than the worldwide average level of Fe in soil (20,000 mg/kg), and this concurs with findings at other communities near mine tailing dams (Antwi-Agyei et al., 2009; Gyamfi et al., 2019; Hadzi et al., 2019). Mensah et al. (2020) explained that arsenopyrite and scorodite are major constituents of Fe in mine tailings, in addition to high concentrations of magnetite and hematite in typical Ghanaian soils. Again, leaching and acid mine drainage of the Pompora mine tailings dam could contribute partly to the high levels of iron in the soils of the surrounding communities (Hammond et al., 2020; Laker, 2023; Zúñiga-Vázquez et al., 2023). More so, the gangue components consisting of iron are not impacted (transformed) during the chemical seeding (reaction) process of gold extraction, thus leaving large concentrations of Fe in mine tailings (Cheng et al., 2014; Kastury et al., 2024). The results also show that the levels of Mn in communities are above regulatory and worldwide average in soil, with values ranging between 2,269.75 mg/kg - 4,911.0 mg/kg (Kabata-Pendias, 2011; USEPA, 2002; Wedepohl, 1995). Although Mn is a micro-nutrient required for enzymatic activity, alleviating oxidative stress and photosynthesis, concentrations above 500 mg/kg are harmful to living organisms (Bihanic et al., 2021). The elevated concentrations of Mn in soils could also be attributed to the humus-rich forest ochrosol found in Obuasi, which has a strong affinity for Mn (Kushwaha et al., 2015). The concentrations of Cu in soil ranged from 47.98 mg/kg to 123.53 mg/kg; however, apart from Obuasi Estate, which recorded the lowest value, all sites had levels above regulatory limits of USEPA (2004), and the average shale value proposed by Wedepohl (1995). More so, the concentrations of Cu observed are greater than reports of mining communities in Ghana (Baah et al., 2023; Mensah & Addai, 2024; Petelka et al., 2019; Wiafe et al., 2022). Although copper is an essential component of metalloenzymes in living organisms, concentrations greater than 50 mg/kg could cause damage to plants and reduce soil microbial community structure and activity (Doku et al., 2024; Mir et al., 2021; Tang et al., 2019). Zinc concentrations in soil ranged bet-

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Table 3. *Concentrations of heavy metals in soil*

Site		Heavy metal concentrations (mg/kg)						
		Fe	Mn	Cu	Zn	As	Cd	Pb
Kyekyewere	Mean	46,751.0	2,283.50	88.63	67.04	61.03	11.83	75.00
	SD	36.75	57.12	7.45	1.50	1.85	0.92	3.14
	Max	46,784.0	2,350.00	95.60	68.90	62.50	12.50	78.90
	Min	46700.00	2,224.00	78.50	65.44	58.50	10.50	71.50
	n	4	4	4	4	4	4	4
Boete	Mean	32,528.25	4,522.75	123.53	123.50	76.98	10.27	85.08
	SD	40.14	20.58	2.43	3.42	1.51	1.68	2.75
	Max	32,586.00	4,550.00	125.90	128.00	78.90	12.50	88.90
	Min	32,500.00	4,500.00	120.50	120.00	75.21	8.58	82.50
	n	4	4	4	4	4	4	4
Kokoteasua	Mean	25,736.00	2,515.00	56.05	55.30	90.93	9.53	91.38
	SD	35.31	14.51	3.01	0.62	1.26	0.67	2.39
	Max	25,775.00	2,529.00	60.30	56.00	92.50	10.45	93.80
	Min	25,700.00	2,495.00	53.40	54.76	89.50	8.90	88.50
	n	4	4	4	4	4	4	4
Bossman	Mean	34,768.25	2,902.75	116.10	72.69	55.41	8.65	77.70
	SD	15.67	42.20	3.86	1.14	1.09	1.08	1.06
	Max	34,788.00	2,950.00	120.50	73.80	56.80	10.20	78.90
	Min	34,750.00	2,850.00	111.40	71.46	54.23	7.71	76.50
	n	4	4	4	4	4	4	4
Tutuka	Mean	42,579.75	4,911.00	111.95	106.38	74.50	9.73	83.50
	SD	24.09	15.30	5.39	2.63	2.27	1.57	1.73
	Max	42,609.00	4,925.00	120.00	110.00	77.00	12.00	85.90
	Min	42,550.00	4,890.00	108.80	104.00	72.21	8.51	81.90
	n	4	4	4	4	4	4	4
Akaposriso	Mean	25,091.00	3,245.75	55.15	57.22	81.23	8.40	72.88
	SD	30.12	24.06	1.26	0.91	1.41	0.34	2.03
	Max	25,120.00	3,278.00	56.50	58.00	82.90	8.90	75.20
	Min	25,050.00	3,225.00	53.80	56.36	70.70	8.11	70.80
	n	4	4	4	4	4	4	4
Samsonkrom 1	Mean	26,823.00	2,482.75	71.25	58.11	77.23	7.92	82.33
	SD	27.98	4.57	0.85	1.31	1.15	0.35	5.45
	Max	26,850.00	2,488.00	72.50	59.50	78.50	8.30	88.00
	Min	26,790.00	2,283.00	70.60	56.70	75.90	7.5	76.90
	n	4	4	4	4	4	4	4
Obuasi Estate	Mean	24,464.75	2,269.75	47.98	54.63	81.08	8.01	70.58
	SD	5.74	11.24	2.82	0.95	1.36	0.26	1.47
	Max	24,472.00	2,283.00	51.90	55.90	82.80	8.30	72.00
	Min	24,458.00	2,257.00	45.40	53.76	79.80	7.69	68.90
	n	4	4	4	4	4	4	4

ween 54.63 mg/kg and 123.50 mg/kg, with most sites recording values less than regulatory limits (Kabatas-Pendias, 2011; USEPA, 2002).The observed levels at Boete and Nyamebekyre are higher than an earlier report by Bempah et al. (2013), who also conducted studies at the Pompora tailings dam. Sphalerite is a mineral found in the Ghanaian ore gangue, contributing significant proportions of zinc in mine

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tailings (Amoakwah et al., 2020; Roussel et al., 2000; Sey & Belford, 2019). Gankhurel et al. (2020) observed a strong association or binding of As and Pb to Fe-Mn oxides in mine tailings, which are predominant in West African gold ore formations. The observed levels of As (55.4 mg/kg – 90.93 mg/kg) and Pb (70.58 mg/kg – 91.38 mg/kg) exceed the world soil, sub-regional averages, and earlier reports of Obuasi (Akoto et al., 2023; Bempah & Ewusi, 2016; Kabata-Pendias, 2011; Taylor, 1964). More so, in tropical climates where higher temperatures occur all year round, the toxic metal ions in the liquid phase of tailings slurry dry up, leaving particulate matter that is liable to wind erosion and rainfall-induced percolation into deeper soil layers and groundwater (Kaninga et al., 2020; Laker, 2023; Nie et al., 2023). Unlike As and Pb, which bind to soil organic matter, Cd binds to clayey particles and water-soluble fractions in mine tailings, thus showing better mobility and bioavailability in mine-impacted soils (Gankhurel et al., 2020; Rinklebe et al., 2019; Zhang et al., 2023). Thus, the continual release of heavy metal contaminants from tailing dams mainly contributes to environmental pollution near mining settlements globally (Chen et al., 2022; Hadzi et al., 2019; Khan et al., 2021; Krasavtseva et al., 2021).

Correlation and Principal Component Analyses

Factor analysis unveiled two major components accounting for 75% of the variation in heavy metal concentrations of soils sampled from communities near the Pompora tailing dam (Table 4). Fe, Cu, Zn, and Cd constituted the first component (51.66%), while Mn, As, and Pb formed the second major component (25.46%). The component analysis results are consistent with earlier findings of gold mine tailings dam-impacted communities (Hadzi et al., 2019; Kazapoe et al., 2022; Mensah & Addai, 2024). Ntiamoah-Agyakwa (1979) explained that the Obuasi gold ore-bearing bodies are associated with manganiferous rocks, of which the latter is considered a contaminant. Galena, chalcopyrite, arsenopyrite, and sphalerite are the minor minerals associated with the pyrite body, which underlie the preponderance of Fe, Cu, As, and Zn minerals in Ghanaian tailings (Bempah et al., 2013; Cuevas et al., 2023; Roussel et al., 2000). Similarly, Fe showed positive correlations with Cu, Cd, Mn, and Zn, but significant positive correlations were observed between Fe-Cd (0.786), Mn-Zn (0.896), and Cu-Zn (Table 5). The correlation between Fe/Cd is consistent with other findings; however, the binding of Cd to oxides of iron forms a relatively less bioavailable complex in mine tailings, thus reducing its movement into higher trophic levels (Liu et al., 2021; Suda and Makino, 2016; Zúñiga-Vázquez et al., 2023).

Table 2
Principal component analysis of heavy metals in soil

Component	Eigen-value	Percentage variance	Heavy metal	Component 1	Component 2
1	3.61626	51.66	Fe	0.428	-0.341
2	1.78215	25.46	Mn	0.376	0.402
3	0.92663	13.24	Cu	0.491	0.004
4	0.49489	7.070	Zn	0.458	0.289
5	0.14969	2.139	As	-0.274	0.570
6	0.03026	0.432	Cd	0.358	-0.176
7	0.00097	0.001	Pb	0.148	0.532

Table 3
Pearson linear correlation of heavy metals in soil

	Fe	Mn	Cu	Zn	As	Cd	Pb
Fe	1						
Mn	0.315	1					
Cu	0.655	0.669	1				
Zn	0.463	**0.896***	**0.842***	1			
As	-0.680	0.029	-0.616	-0.167	1		
Cd	**0.786***	0.196	0.441	0.422	-0.317	1	
Pb	-0.007	0.334	0.268	0.355	0.371	0.203	1

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Pollution Assessment

Assessing the extent of heavy metal pollution in soils of communities around mine tailings depicts mineralogical exploration's environmental impact (Kaninga et al., 2020). The pollution load index indicated significant levels of heavy metal contamination in the top soils of all the communities surrounding the Pompora tailings dam (Table 6). Specifically, As and Cd recorded very high soil contamination factors from all the communities examined. Similarly, the geo-accumulation index (Table 7) and enrichment factors (Table 8) indicated moderate – strong and severe pollution for these metals, respectively, which are in consonance with previous research on soils within the environs of the Pompora tailings dam (Akoto et al., 2023; Amonoo-Neizer et al., 1996; Antwi-Agyei et al., 2009; Bempah & Ewusi, 2016). Moreover, the elevated status of Cd contamination is attributable to the mineralogical presence and seeding solutions during the extraction process (Gankhurel et al., 2020; Ntiamoah-Agyakwa, 1979; Shen et al., 2019). The pollution load index indicated significant heavy metal contamination of soils in communities within the catchment area of the Pompora tailing dam (Cuevas et al., 2023; Shaheen et al., 2023; Tomlinson et al., 1980).

Table 6 *Contamination factor and pollution load index (PLI) of heavy metals*

	Contamination factor of heavy metals							PLI
Site	Fe	Mn	Cu	Zn	As	Cd	Pb	
Kyekyewere	2.34	4.68	2.30	0.96	8.97	59.13	2.78	4.47
Boete	1.63	9.27	3.21	1.76	11.32	51.35	3.15	5.52
Kokoteasua	1.29	5.15	1.46	0.79	13.37	47.64	3.38	4.00
Bossman	1.74	5.95	3.02	1.04	8.15	43.26	2.88	4.42
Nyamebekyere	2.13	10.06	2.91	1.52	10.96	48.64	3.09	5.52
Tutuka	1.26	6.65	1.43	0.82	11.95	42.01	2.70	3.88
Akaporiso	1.34	5.09	1.85	0.83	11.36	39.61	3.05	3.93
Obuasi Estate	1.22	4.65	1.25	0.78	11.92	40.06	2.61	3.54

Table 7 *Geo-accumulation index of heavy metals in soil*

Site	Geo-accumulation index						
	Fe	Mn	Cu	Zn	As	Cd	Pb
Kyekyewere	0.640	1.641	0.618	-0.647	2.581	5.301	0.889
Boete	0.117	2.627	1.097	0.234	2.916	5.097	1.071
Kokoteasua	-0.221	1.781	-0.043	-0.925	3.156	4.989	1.174
Bossman	0.213	1.988	1.007	-0.531	2.442	4.850	0.940
Nyamebekyere	0.505	2.746	0.955	0.019	2.869	5.019	1.044
Tutuka	-0.258	2.149	-0.066	-0.876	2.993	4.808	0.848
Akaporiso	-0.161	1.762	0.303	-0.854	2.921	4.723	1.023
Obuasi Estate	-0.294	1.633	-0.268	-0.943	2.991	4.739	0.801

Table 8 *Enrichment factor of heavy metals in soil*

	Enrichment factor					
Site	Mn	Cu	Zn	As	Cd	Pb
Kyekyewere	6.56	9.38	1.95	46.18	178.97	6.68
Boete	9.04	9.10	2.50	40.53	108.15	5.27
Kokoteasua	3.98	3.27	0.89	37.88	79.38	4.48
Bossman	6.20	9.14	1.57	31.18	97.38	5.14
Nyamebekyere	12.85	10.79	2.82	51.35	134.08	6.77
Tutuka	5.00	3.13	0.89	32.99	68.25	3.48
Akaporiso	4.09	4.33	0.97	33.53	68.79	4.21
Obuasi Estate	3.41	2.66	0.83	32.11	63.46	3.29

Health Risk Assessment

Tailing dam failures release volumes of hazardous metals into the environment; however, existing facilities tend to contaminate surrounding soils gradually, a condition that introduces severe health implications such as cancer, skin diseases, and organ and systemic failures (Hadzi et al., 2019; Islam and Murakami, 2021; Kaninga et al., 2020; Kiran et al., 2021; Zhang et al., 2023). Human health risk assessment is relevant in controlling the impact of environmental hazards that may accrue through heavy metal contamination (Antoniadis et al., 2019; Chen et al., 2022; Doku et al., 2023; Penteado et al., 2021). The hazard quotient of heavy metals in children, adult females, and males from ingestion of soils is shown in Fgure 2. The hazard quotient (HQ) for children was the highest, followed by adult females and adult males (Tables 9, 10, 11). Specifically, the HQ for children was above unity for Mn at Boete and Nyamebekyere. Again, the HQ was above unity for As in all communities within the catchment area of the Pompora tailing dam. This outcome is consistent with earlier studies, which suggest that children could experience adverse health effects by ingesting soils contaminated with heavy metals (Doku et al., 2023; Li et al., 2015; Mensah and Addai, 2024; Shen et al., 2019).).

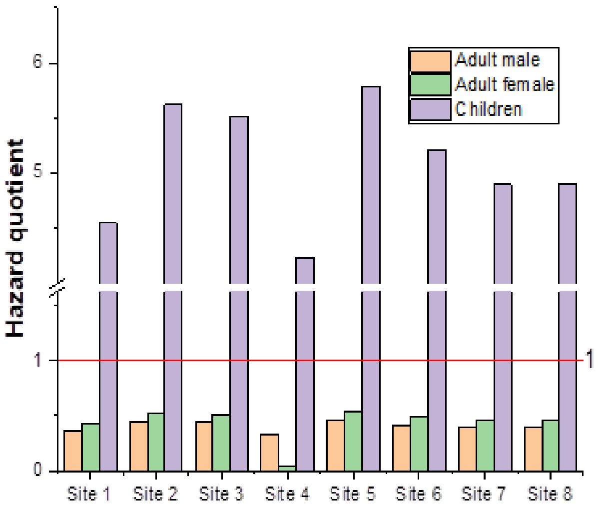

Figure 2. *Hazard quotient of adults (male and female) and children. Site1 (Kyekewere), Site 2 (Boete), Site 3 (Kokoteasua), Site 4 (Bossman), Site 5 (Nyamebekyere), Site 6 (Tutuka), Site 7 (Akaporiso), Site 8 (Obuasi Estate).*

Table 9
Hazard quotient of heavy metals in adult males

Site	Fe	Mn	Cu	Zn	As	Cd	Pb
Kyekyewere	0.067	0.050	0.002	0.000	0.205	0.012	0.022
Boete	0.047	0.099	0.003	0.000	0.258	0.010	0.024
Kokoteasua	0.037	0.055	0.001	0.000	0.305	0.010	0.026
Bossman	0.050	0.064	0.003	0.000	0.186	0.009	0.022
Nyamebekyere	0.061	0.108	0.003	0.000	0.250	0.010	0.024
Tutuka	0.036	0.071	0.001	0.000	0.273	0.008	0.021
Akaporiso	0.039	0.054	0.002	0.000	0.259	0.008	0.024
Obuasi Estate	0.035	0.050	0.001	0.000	0.272	0.008	0.020

Table 10
Hazard quotient of heavy metals in adult females

Site	Fe	Mn	Cu	Zn	As	Cd	Pb
Kyekyewere	0.079	0.059	0.003	0.000	0.240	0.014	0.025
Boete	0.055	0.116	0.004	0.000	0.303	0.012	0.029
Kokoteasua	0.043	0.065	0.002	0.000	0.358	0.011	0.031
Bossman	0.041	0.003	0.000	0.000	0.000	0.000	0.000
Nyamebekyere	0.072	0.126	0.003	0.000	0.293	0.011	0.028
Tutuka	0.042	0.083	0.002	0.000	0.320	0.010	0.025
Akaporiso	0.045	0.064	0.002	0.000	0.304	0.009	0.028
Obuasi Estate	0.041	0.058	0.001	0.000	0.319	0.009	0.024

Table 11
Hazard quotient of heavy metals in children

Site	Fe	Mn	Cu	Zn	As	Cd	Pb
Kyekyewere	0.854	0.635	0.028	0.003	2.601	0.151	0.274
Boete	0.594	1.257	0.039	0.005	3.281	0.131	0.311
Kokoteasua	0.470	0.699	0.018	0.002	3.875	0.122	0.334
Bossman	0.635	0.807	0.037	0.003	2.361	0.111	0.284
Nyamebekyere	0.778	1.365	0.036	0.005	3.175	0.124	0.305
Tutuka	0.458	0.902	0.018	0.002	3.462	0.107	0.266
Akaporiso	0.490	0.690	0.023	0.002	3.291	0.101	0.301
Obuasi Estate	0.447	0.631	0.015	0.002	3.455	0.102	0.258

In summary, although some studies depict the potential hazards in adults as a result of metal contamination in communities within the catchment areas of tailing dams, this study concurs with findings suggesting a more significant adverse health impact in children (Antoniadis et al., 2019; Ghosh et al., 2023; Hadzi et al., 2019; Hou et al., 2023; Mensah et al., 2020). The hazard index, which sums up the HQs for different metals for a community, followed the trend: Nyamebekyere > Boete > Kokoteasua > Tutuka > Obuasi Estate > Akaporiso > Kyekyewere > Bossman (Fig. 3).

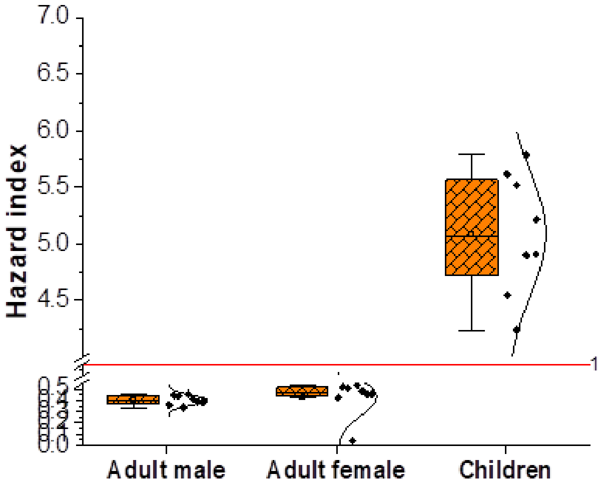

Figure 3. *Hazard index of adults (male and female) and children*

Similar to the findings of Amonoo-Neizer et al. (1996), this study observes that communities near the tailing treatment dam had top soils containing higher concentrations of heavy metals. Although Nyamebekyere is farthest from the Pompora tailing dam, it recorded the highest levels of metal contamination, which may result from its closeness to the former tailing treatment plant (Amonoo-Neizer et al., 1996; Boateng et al., 2012; Osei Akoto et al., 2018). Similarly, the marked soil contamination at Boete and Kokoteasua is traceable to their proximity to tailing dams operated by the Anglo Gold Ashanti mining firm (Boateng et al., 2012).

Conclusions

This study investigated the extent of heavy metal contamination and associated health effects within the Ghanaian mining settlement of Obuasi. The Fe, Mn, As, Pb and Cd levels in the communities' surface soil are above the global average and regional crustal background, suggesting anthropogenic impact. Furthermore, pollution indicators revealed severe heavy metal enrichment in these communities from mineralogical deposits and mining activities. Assessment of health risks via ingestion of surface soil from these communities showed that children are most prone to adverse health ramifications, with the hazard index unveiling potential health challenges for communities close to tailing dams within Obuasi. Thus, the study contributes information on the current status of heavy metal pollution in communities near the Pompora tailing dam for environmental monitoring, management, and potential remedial action.

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References

ABRAHIM G.M.S., PARKER R.J. (2008) Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki Estuary, Auckland, New Zealand. Environmental Monitoring and Assessment, 136(1–3):227–238. https://doi.org/10.1007/s10661- 007-9678-2

AGYEMAN P.C., JOHN K., KEBONYE N.M., BORŮVKA L., VAŠÁT, R. (2023) Combination of enrichment factor and positive matrix factorization in the estimation of potentially toxic element source distribution in agricultural soil. Environmental Geochemistry and Health, 45(5) 2359–2385.https://doi.org/10.1007/s10653-022-01348-z

AKOTO O., YAKUBU S., OFORI L. A., BORTEY-SAM N., BOADI, N. O., HORGAH J., SACKEY L. N. A. (2023) Multivariate studies and heavy metal pollution in soil from gold mining area. Heliyon, 9(1). https://doi.org/10.1016/j.heliyon.2022.e12661

AMOAKWAH E., AHSAN S., RAHMAN M. A., ASAMOAH E., ESSUMANG D. K., ALI M., ISLAM K. R. (2020) Assessment of Heavy Metal Pollution of Soil-water-vegetative Ecosystems Associated with Artisanal Gold Mining. Soil and Sediment Contamination, 29(7):788–803. https://doi.org/10.1080/15320383.2020.1777936

AMONOO-NEIZER E.H., NYAMAH D., BAKIAMOH S. B. (1996) Mercury and arsenic pollution in soil and biological samples around the mining town of Obuasi, Ghana. Water, Air, and Soil Pollution, 91(3–4): 363–373. https://doi.org/10.1007/BF00666270

ANGULO E. (1996) The Tomlinson Pollution Load Index applied to heavy metal, "mussel- watch" data: A useful index to assess coastal pollution. Science of the Total Environment, 187(1):19–56. https://doi.org/10. 1016/0048-9697(96)05128-5

ANTONIADIS V., SHAHEEN S. M., LEVIZOU E., SHAHID M., NIAZI N. K., VITHANAGE M., OK Y. S., BOLAN N., RINKLEBE J. (2019) A critical prospective analysis of the potential toxicity of trace element regulation limits in soils worldwide: Are they protective concerning health risk assessment? - A review. Environ-ment International, 127:819–847. https://doi.org/10.1016/j.envint. 2019.03.039

ANTWI-AGYEI P., HOGARH J. N., FOLI G. (2009) Trace elements contamination of soils around gold.pdf. African Journal of Environmental Science and Technology, 3(11):353–359.

ARAUJO F.S.M., TABORDA-LLANO I., NUNES E.B., SANTOS R.M. (2022) Recycling and reuse of mine tailings: A review of advancements and their implications. Geosciences, 12(9). https://doi.org/10.3390/geosciences12090319

AZAM S., LI Q. (2010) Tailings dam failures: A review of the last one hundred years. Geotechnical News, 28(4):50–53.

AZIZI M., FAZ A., ZORNOZA R., MARTÍNEZ-MARTÍNEZ S., SHAHROKH V., ACOSTA J.A. (2022) Environmental pollution and depth distribution of metal(loid)s and rare earth elements in mine tailing. Journal of Environmental Chemical Engineering, 10(3):107526. https://doi.org/10.1016/j.jece.2022.107526

BAAH D. S., FOSU-ASANTE D., KOFI AGYEKUM C., MAWULI EDZESI W., ACHEAMPONG E. B. (2023) Geochemical Assessment of Metals in Soils and Food Crops Around Alluvial Gold Mining in Abuakwa South Municipal, Ghana. Soil and Sediment Contamination: An International Journal, 1–17. https://doi.org/10.1080/15320383. 2023.2225624

BAAH-ENNUMH T.Y., ADOM-ASAMOAH G. (2019) Land use challenges in mining communities - the case of tarkwa-nsuaem municipality. Environment and Ecology Research, 7(3): 139–152. https://doi.org/10.13189/eer.2019.070304

BANSO A.K., AMANKWAH R.K., NDUR S.A. (2020) Seasonal and temporal distribution of arsenic. International Journal of Research And Scientific Innovation, 7(9):286-294.

BEMPAH C.K., EWUSI A. (2016) Heavy metals contamination and human health risk assessment around Obuasi gold mine in Ghana. Environmental Monitoring and Assessment, 188(5).https://doi.org/10.1007/s10661-016-5241-3

BEMPAH C.K., EWUSI A., OBIRI-YEBOAH S., ASABERE B., MENSAH F., BOATENG J., VOIGT H. (2013) Distribution of arsenic and heavy metals from mine Tailings dams at Obuasi Municipality of Ghana. 05:61–70.

BHARTI, R., & SHARMA, R. (2021). Effect of heavy metals: An overview. Materials Today: Proceedings, 51, 880–885. https://doi.org/10.1016/j.matpr.2021.06.278

BIHANIC C., PETIT E., PERROT R., CASES L., GARCIA A., PELISSIER F., POULLAIN C., RIVARD C., HOSSAERT-MCKEY M., MCKEY D., GRISON C. (2021) Manganese distribution in the Mn-hyperaccumulator Grevillea meisneri from New Caledonia. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-03151-9

BOATENG E., DOWUONA G. N., FOLI G. (2012) Geochemical Assessment of the Impact of Mine Tailings Reclamation on the Quality of Soils at AngloGold Concession.https://www.researchgate.net/publication/264045842

CHENG K., TIAN H. Z., ZHAO D., LU L., WANG Y., CHEN J., LIU X. G., JIA W. X., HUANG Z. (2014) Atmospheric emission inventory of cadmium from anthropogenic sources. International Journal of Environmental Science and Technology, 11(3): 605–616. https://doi.org/10.1007/s13762-013-0206-3

CHEN R., HAN L., LIU Z., ZHAO Y., LI R., XIA L., FAN Y. (2022) Assessment of Soil-Heavy Metal Pollution and the Health Risks in a Mining Area from Southern Shaanxi Province, China. Toxics, 10(7). https://doi.org/10.3390/toxics10070385

CUEVAS J. G., FAZ A., MARTÍNEZ-MARTÍNEZ S., GABARRÓN M., BELTRÁ J. C., MARTÍNEZ J., ACOSTA J. A. (2023) Spatial distribution and pollution evaluation in dry riverbeds affected by mine tailings. Environmental Geochemistry and Health, 0123456789. https://doi.org/10.1007/s10653-022-01469-5

DARKO G., DODD M., NKANSAH M. A., ADUSE-POKU Y., ANSAH E., WEMEGAH D. D., BORQUAYE L.S. (2017) Distribution and ecological risks of toxic metals in the topsoils in the Kumasi metropolis, Ghana. Cogent Environmental Science, 3(1). https://doi.org/10.1080/23311843.2017.1354965

DOKU E. T., ADJEI-HINNEH G., ANING J. (2023) Playground Soil Contamination with Heavy Metals and Associated Health Risks of Children in Schools Located in the Sunyani-East Municipality of Ghana. Environment Asia, 16(1):73–86. https://doi.org/10.14456/ea.2023.7

DOKU E. T., SYLVERKEN A. A., BELFORD J. D. E. (2024) Rhizosphere microbiome of plants used in phytoremediation of mine tailing dams. International Journal of Phytoremediation. https://doi.org/10.1080/15226514.2024.2301994

FURAL Ş., KÜKRER S., CÜREBAL İ. (2020) Geographical information systems based ecological risk analysis of metal accumulation in sediments of İkizcetepeler Dam

Lake (Turkey). Ecological Indicators, 119. https://doi.org/10.1016/j.ecolind.2020.106784

FU Z., XI S. (2020) The effects of heavy metals on human metabolism. Toxicology Mechanisms and Methods, 30(3): 167–176.https://doi.org/10.1080/15376516.2019.1701594

GANKHUREL B., FUKUSHI K., AKEHI A., TAKAHASHI Y., ZHAO X., KAWASAKI K. (2020) Comparison of Chemical Speciation of Lead, Arsenic, and cadmium in contaminated soils from a historical mining site: implications for different mobilities of heavy metals. ACS Earth and Space Chemistry, 4(7):1064–1077. https://doi.org/10.1021/acsearthspacechem.0c00087

GHOSH S., BANERJEE S., PRAJAPATI J., MANDAL J., MUKHERJEE A., BHATTACHARYYA P. (2023) Pollution and health risk assessment of mine tailings contaminated soils in India from toxic elements with statistical approaches. Chemosphere, 324:138267. https://doi.org/10.1016/j.chemosphere.2023.138267

GUIMARÃES R.N., MOREIRA V.R., MARCIANO DE OLIVEIRA L.V., AMARAL M.C.S. (2023) A conceptual model to establish preventive and corrective actions to guarantee water safety following scenarios of tailing dam failure. Journal of Environmental Management, 344. https://doi.org/10.1016/j.jenvman.2023.118506

GYAMFI E., APPIAH-ADJEI E. K., ADJEI K. A. (2019) Potential heavy metal pollution of soil and water resources from artisanal mining in Kokoteasua, Ghana. Groundwater for Sustainable Development, 8:450–456. https://doi.org/10.1016/j.gsd.2019.01.007

HADZI G.Y., AYOKO G.A., ESSUMANG D.K., OSAE S.K.D. (2019) Contamination impact and human health risk assessment of heavy metals in surface soils from selected major mining areas in Ghana. Environmental Geochemistry and Health, 41(6):2821–2843. https://doi.org/10. 1007/s10653-019-00332-4

HAMMOND C.M., ROOT R.A., MAIER R.M., CHOROVER J. (2020) Arsenic and iron speciation and mobilization during phytostabilization of pyritic mine tailings. Geochimica et Cosmochimica Acta, 286:306–323. https://doi.org/ 10.1016/j.gca.2020.07.001

HOU Y., ZHAO Y., LU J., WEI Q., ZANG L., ZHAO X. (2023) Environmental contamination and health risk assessment of potentially toxic trace metal elements in soils near gold mines – A global meta-analysis. Environmental Pollution, 330:121803. https://doi.org/10.1016/j.envpol.2023.121803

HUANG L., BAUMGARTL T., MULLIGAN D. (2012) Is rhizosphere remediation sufficient for sustainable revegetation of mine tailings? Annals of Botany, 110(2), 223–238. https://doi.org/10.1093/aob/mcs115

ISLAM K., MURAKAMI S. (2021) Global-scale impact analysis of mine tailings dam failures: 1915–2020. Global Environmental Change, 70: 102361. https://doi.org/10.1016/ j.gloenvcha.2021.102361

JAYAPAL A., CHATERJEE T., SAHARIAH B. P. (2023) Bioremediation techniques for the treatment of mine tailings: A review. In Soil Ecology Letters, 5(2). https://doi.org/10.1007/s42832-022-0149-z

KABATA-PENDIAS A. (2011) Trace elements in soils and plants (4th Editio). CRC Press Taylor & Francis Group, 6000 Broken Sound Parkway NW Vol. 53 Issue 9.

KANINGA B.K., CHISHALA B.H., MASEKA K.K., SAKALA G.M., LARK M.R., TYE A., WATTS M.J. (2020) Review: mine tailings in an African tropical environment—mechanisms for the bioavailability of heavy metals in soils. Environmental Geochemistry and Health, 42(4): 1069–1094. https://doi.org/10.1007/s10653-019-00326-2

KASTURY F., BESEDIN J., BETTS A.R., ASAMOAH R., HERDE C., NETHERWAY P., TULLY J., SCHECKEL K.G., JUHASZ A.L. (2024) Arsenic, cadmium, lead, antimony bioaccessibility and relative bioavailability in legacy gold mining waste. Journal of Hazardous Materials, 469. https://doi.org/10.1016/j.jhazmat.2024.133948

KAZAPOE R.W., AMUAH E.E.Y., DANKWA P. (2022) Sources and pollution assessment of trace elements in soils of some selected mining areas of southwestern Ghana. Environmental Technology and Innovation, 26:102329. https://doi.org/10.1016/j.eti.2022.102329

KHAN S., NAUSHAD M., LIMA E.C., ZHANG S., SHAHEEN S.M., RINKLEBE J. (2021) Global soil pollution by toxic elements: Current status and future perspectives on the risk assessment and remediation strategies – A review. Journal of Hazardous Materials, 417:0–2. https://doi.org/10.1016/j.jhazmat.2021.126039

BHARTI R., SHARMA R. (2022) Effect of heavy metals: An overview. Materials Today: Proceedings, 51:880-885. https://doi.org/10.1016/j.matpr.2021.06.278

KRASAVTSEVA E., MAKSIMOVA V., MAKAROV D. (2021) Conditions affecting the release of heavy and rare earth metals from the mine tailings kola subarctic. Toxics, 9(7):1–19. https://doi.org/10.3390/toxics9070163

KUMI S., KIDIDO J. K., SACKEY E. K. (2024) Drivers and drags of speculative land developments in a prospective mining landscape, Ghana. The Extractive Industries and Society, 17:101443. https://doi.org/10.1016/j.exis.2024.101443

KUSHWAHA A., RANI R., KUMAR S., GAUTAM A. (2015) Heavy metal detoxification and tolerance mechanisms in plants: Implications for phytoremediation. Environmental Reviews, 24(1):39–51. https://doi.org/10.1139/er-2015-0010

KWANING E., ATTEH E. (2022) Review on Effects of Mining in Ghana: The Case of Obuasi Municipality. Asian

Research Journal of Arts & Social Sciences, 50–57. https://doi.org/10.9734/arjass/2022/v18i4402

LAKER M. C. (2023) Environmental Impacts of Gold Mining—With Special Reference to South Africa. Mining, 3(2)205–220. https://doi.org/10.3390/mining3020012

LI P., LIN C., CHENG H., DUAN X., LEI K. (2015) Contamination and health risks of soil heavy metals around a lead/zinc smelter in southwestern China. Ecotoxicology and Environmental Safety, 113: 391–399. https://doi.org/10.1016/j.ecoenv.2014.12.025

LIU J., ZHU R., MA L., FU H., LIN X., PARKER S. C., MOLINARI M. (2021) Adsorption of phosphate and cadmium on iron (oxyhydr)oxides: A comparative study on ferrihydrite, goethite, and hematite. Geoderma, 383. https://doi.org/10.1016/j.geoderma.2020.114799

MENSAH A. K., ADDAI P. (2024) Contamination with Cd, Cu, Hg, Sb, Se and Ti in abandoned and active mining sites in Ghana: assessment of their potential soil and human health risks. Environmental Advances, 100500. https://doi.org/10.1016/j.envadv.2024.100500

MENSAH A. K., MAHIRI I. O., OWUSU O., MIREKU O. D., WIREKO I., KISSI E. A. (2015) Environmental Impacts of Mining: A Study of Mining Communities in Ghana. 3(3):81–94. https://doi.org/10.12691/aees-3-3-3

MENSAH A. K., MARSCHNER B., ANTONIADIS V., STEMN E., SHAHEEN S. M., RINKLEBE J. (2021) Human health risk via soil ingestion of potentially toxic elements and remediation potential of native plants near an abandoned mine spoil in Ghana. Science of the Total Environment, 798:149272. https://doi.org/10.1016/j.scitotenv.2021.149272

MENSAH A. K., MARSCHNER B., SHAHEEN S. M., WANG J., WANG S. L., RINKLEBE J. (2020) Arsenic contamination in abandoned and active gold mine spoils in Ghana: Geochemical fractionation, speciation, and assessment of the potential human health risk. Environmental Pollution, 261:114116. https://doi.org/10.1016/j.envpol.2020.114116

MIR A. R., PICHTEL J., HAYAT S. (2021) Copper: uptake, toxicity and tolerance in plants and management of Cu-contaminated soil. BioMetals, 34(4), 737–759. https://doi.org/10.1007/s10534-021-00306-z

MÜLLER G. (1969) Index of geoaccumulation in sediments of the Rhine River. Geojournal, 2(24):108–118.

NIE W., LI C., HU J., SAFFARI P., WANG W., LUO M. (2023) Spatial variation of physical and mechanical properties of tailings under different rainfall intensities and the interacttion pattern. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 9(1). https://doi.org/10.1007/s40948-023-00625-0

NKANSAH F. K., BELFORD E. J. D. (2017) Heavy Metals Accumulation by Indigenous Plants Growing in Contaminated Soil in a Gold Mining Area in Ghana. Journal of Natural Sciences Research, 7(24):41–47. https://www.iiste.org/Journals/index.php/JNSR/article/view/40117

NTIAMOAH-AGYAKWA Y. (1979) Relationship between gold and manganese mineralizations in the Birimian of Ghana, West Africa. Geological Magazine, 116(5):345–352. https://doi.org/10.1017/S0016756800043983

OJUEDERIE O. B., BABALOLA O. O. (2017) Microbial and plant-assisted bioremediation of heavy metal polluted environments: A review. International Journal of Environmental Research and Public Health, 14(12). https://doi.org/10.3390/ijerph14121504

OKOTO S., BORTEY-SAM N., SHOUTA M.M. NAKAYAMA, YOSHINORI IKENAKA, ELVIS BAIDOO, JOSEPH APAU, JEMIMA TIWAA MARFO, MAYUMI ISHIZUKA. (2018) Characterization spatial variation and risk assessment of heavy metals and a metalloid in surface. Journal of Health and Pollution, 8(19):180902. https://doi.org/10.5696/2156-9614-8.19.180902

OWEN J. R., KEMP D., LÈBRE SVOBODOVA K., PÉREZ MURILLO G. (2020) Catastrophic tailings dam failures and disaster risk disclosure. International Journal of Disaster Risk Reduction, 42:101361. https://doi.org/10.1016/j.ijdrr.2019.101361

PARLAK M., TUNÇAY T., BOTSOU F. (2022) Heavy Metals in Soil and Sand from Playgrounds of Çanakkale City (Turkey), and Related Health Risks for Children. Sustainability, 14(3). https://doi.org/10.3390/su14031145

PENTEADO J. O., BRUM R. DE L., RAMIRES P. F., GARCIA E. M., DOS SANTOS M., DA SILVA JÚNIOR F. M. R. (2021) Health risk assessment in urban parks soils contaminated by metals, Rio Grande city (Brazil) case study. Ecotoxicology and Environmental Safety, 208. https://doi.org/10.1016/j.ecoenv.2020.111737

PETELKA J., ABRAHAM J., BOCKREIS A., DEIKUMAH J. P., ZERBE S. (2019) Soil Heavy Metal(loid) Pollution and Phytoremediation Potential of Native Plants on a Former Gold Mine in Ghana. Water, Air and Soil Pollution, 230(11). https://doi.org/10.1007/s11270-019-4317-4

RAI P. K., LEE S. S., ZHANG M., TSANG Y. F., KIM K. H. (2019) Heavy metals in food crops: Health risks, fate, mechanisms, and management. Environment International, 125:365–385.https://doi.org/10.1016/j.envint.2019.01.067

RINKLEBE J., ANTONIADIS V., SHAHEEN S. M., ROSCHE O., ALTERMANN M. (2019) Health risk assessment of potentially toxic elements in soils along the Central Elbe River, Germany. Environment International, 126:76–88. https://doi.org/10.1016/j.envint.2019.02.011

ROUSSEL C., BRIL H., & FERNANDEZ, A. (2000). Arsenic Speciation: Involvement in Evaluation of Environ-

DOI: 10.6092/issn.2281-4485/20002

mental Impact Caused by Mine Wastes. Eqa-International Journal of Environmental Quality, 29(1):182–188. https://doi.org/10.2307/1937348

SEY E., BELFORD E. J. (2019) Levels of Heavy Metals and Contamination Status of a Decommissioned Tailings Dam in Ghana. Journal of Environmental Quality, 35:33–50. https://doi.org/10.6092/issn.2281-4485/9060

SHAHEEN M. E., TAWFIK W., MANKOLA A. F., GAGNON J. E., FRYER B. J., EL-MEKAWY F. M. (2023) Assessment of contamination levels of heavy metals in the agricultural soils using ICP-OES. Soil and Sediment Contamination, 32(6):665–691. https://doi.org/10.1080/15320383.2022.2123448

SHAHEEN S.M., ANTONIADIS V., KWON E., SONG H., WANG S. L., HSEU Z.Y., RINKLEBE J. (2020) Soil contamination by potentially toxic elements and the associated human health risk in geo- and anthropogenic contaminated soils: A case study from the temperate region (Germany) and the arid region (Egypt). Environmental Pollution, 262. https://doi.org/10.1016/j.envpol.2020.114312

SHEN Z., XU D., LI L., WANG J., SHI X. (2019) Ecological and health risks of heavy metal on farmland soils of mining areas around Tongling City, Anhui, China. Environmental Science and Pollution Research, 26(15):15698–15709. https://doi.org/10.1007/s11356-019-04463-0

SOLEIMANI H., MANSOURI B., KIANI A., OMER A. K., TAZIK M., EBRAHIMZADEH G., SHARAFI K. (2023) Ecological risk assessment and heavy metals accumulation in agriculture soils irrigated with treated wastewater effluent, river water, and well water combined with chemical fertilizers. Heliyon, 9(3):e14580. https://doi.org/10.1016/j.heliyon.2023.e14580

SUDA A., MAKINO T. (2016) Functional effects of manganese and iron oxides on the dynamics of trace elements in soils with a special focus on arsenic and cadmium: A review. Geoderma, 270:68–75. https://doi.org/10.1016/j.geoderma.2015.12.017

TANG J., ZHANG J., REN L., ZHOU Y., GAO J., LUO L., YANG Y., PENG Q., HUANG H., CHEN A. (2019) Diagnosis of soil contamination using micro-biological indices: A review on heavy metal pollution. Journal of Environmental Management, 242:121–130. https://doi.org/10.1016/j.jenvman.2019.04.061

TAYLOR S. R. (1964) Abundance of chemical elements in the continental crust: a new table. Geochimica et Cosmochimica Acta, 28(8):1273-1285.

TOMLINSON D.L., WILSON J.G., HARRIS C.R., JEFFREY D.W. (1980) Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index (Vol. 33).

TUME P., ACEVEDO V., ROCA N., FERRARO F. X., BECH J. (2022) Potentially toxic elements concentrations in schoolyard soils in the city of Coronel, Chile. Environmental Geochemistry and Health, 44(5):1521–1535. https://doi.org/10.1007/s10653-021-00909-y

TUREKIAN K. K., WEDEPOHL K. H. (1961) Distribution of the Elements in Some Major Units of the Earth's Crust. Bulletin Geological Society of America, 72(February):175–192. https://doi.org/10.1130/0016-7606(1961)

USEPA. (2002) Supplemental Guidance for developing soil screening levels for Superfund sites. Office of Solid Waste and Emergency Response (OSWER). United States Environmental Protection Agency, December, 1–187. https://nepis.epa.gov/Exe/ZyPDF.cgi/91003IJK.PDF?Dockey=91003IJK.PDF

WEDEPOHL K.H. (1995) The composition of the continental crust. Geochimica et Cosmochimica Acta, 59(7):1217-1232.

WEISSMANNOVÁ H.D., MIHOČOVÁ S., CHOVANEC P., PAVLOVSKÝ J. (2019) Potential ecological risk and human health risk assessment of heavy metal pollution in industrial affected soils by coal mining and metallurgy in Ostrava, Czech Republic. International Journal of Environmental Research and Public Health, 16(22). https://doi.org/10.3390/ijerph16224495

WIAFE S., DUNCAN S. F. H., EBENEZER B., BAAKO S. Y. (2022) Pollution Risk Analysis of Heavy Metals at Illegal Mining Sites at Atiwa East District, Ghana. Current Research in Geoscience, 12(1):1–10. https://doi.org/10.3844/ajgsp.2022.1.10

YAHAYA S.M., ABUBAKAR F., ABDU N. (2021) Ecological risk assessment of heavy metal-contaminated soils of selected villages in Zamfara State, Nigeria. SN Applied Sciences, 3(2): 1–13. https://doi.org/10.1007/s42452-021-04175-6

ZHANG J., LIU Y., HONG S., WEN M., ZHENG C., LIU P. (2023) Speciation Analysis and Pollution Assessment of Heavy Metals in Farmland Soil of a Typical Mining Area: A Case Study of Dachang Tin Polymetallic Ore, Guangxi. Applied Sciences, 13(2). https://doi.org/10.3390/app13020708

ZÚÑIGA-VÁZQUEZ D., ARMIENTA M.A., CRUZ O., AGUAYO A., PÉREZ-MARTÍNEZ I., MORALES-ARREDONDO J.I. (2023) Edaphic properties as pieces of evidence of tailings deposit on soils. Environmental Geochemistry and Health, 45(12):9175–9197. https://doi.org/10.1007/s10653-023-01657-x